SYSTEM ANALYSIS FOR PROGRESS AND INNOVATION IN ENERGY TECHNOLOGIES FOR INTEGRATED ASSESSMENT

Research Project DG RES, 5th Framework Programme

Contract N° ENK6-CT-2002-00615
Partners: ICCS.NTUA, LEPII.EPE, ECN, KUL, PSI, IER, IIASA

PART 2

–DETAILED FINAL REPORT–

Athens, December 2005

table of contents

A. Introduction

The SAPIENTIA project addresses the issue of energy systems analysis by considering driving forces that influence energy technology improvement and in particular the role of R&D in inducing and accelerating it. The project's major ambition is the extension of technology dynamics analysis to a point where it can serve directly in support of R&D portfolio exploration. The analysis covers some of the most important technologies-candidates for community R&D support, incorporates learning processes and technological spillovers and considers a wide range of R&D policy objectives including traditional economic, environmental and a selection of indicators addressing the very topical but often intractable aims of Sustainable Development. Taking into account that R&D strategy evolves in a context of uncertainty, the project undertakes the measurement of interconnected risks in order to incorporate them in a decision support tool designed to assist in the quantitative and systematic exploration of R&D options.

SAPIENTIA is the natural continuation of the SAPIENT project (already completed within the Fifth Framework Programme) whose main achievement has been the demonstration of a way for building a tool for integrated policy assessment. The approach has proved to be fertile providing useful insights for quantitative R&D policy exploration in pursuit of multiple objectives in the presence of uncertainties. SAPIENTIA concentrates on the decision support aspects of SAPIENT and in this sense is much more focused in scope. It also expands significantly the scope by introducing more technologies (candidates for R&D support), describing more fully and operationally spillovers between technologies, enlarging the set of objectives, expanding the policy exploration exercises to the longer term, addressing issues of the efficacy of R&D and Demonstration (D&D) and extends and synthesises technology dynamics results in order to make them useful for actual R&D budgeting policy exploration.

The work presented in SAPIENTIA has been structured around the consolidation and further elaboration of the recent advancements of research in energy systems analysis regarding the dynamics of technical change. In SAPIENTIA, scenarios, cost evaluations and policy assessment are performed using advanced models, which integrate the effects that RTD policy exerts on technology progress. Previous research has shown that the consideration of such a mechanism has considerable implications on shaping the policy, the evaluation of costs and the assessment of the potential of technology development in the markets. Resulting expertise has shown that energy and environmental (especially climate change) strategies have to be substantially reconsidered when evaluated in the presence of induced technological change.

The project delivers quantified information and analysis regarding the system-wide aspects of key energy technologies (both in power and non-power generating sectors) in the framework of the interplay between energy and RTD policy, policy instruments, sustainable development targets (global warming, security of energy supply, ecosystem effects, competitiveness etc.) and technological improvement. Moreover, the project goes one step further to provide results on RTD priorities, portfolio allocation, innovation policy, analytical and quantified results which illustrate the mechanisms of induced technological progress and energy and emission projections for the EU and the World. The latter includes evaluations of impacts on sustainable development under liberalised energy markets for the longer term (up to 2050).

Objectives and Methodology of the SAPIENTIA Project

Technological change is widely recognised as a major driver of economic growth. In recent years also the notion has developed that targeted technological development is one of the main means in an increasingly liberalised world economy to reconcile economic ambitions with 'externality' considerations such as environmental objectives and the pursuit of Sustainable Development in general. This implies that the assessment of future trajectories of energy systems is particularly meaningful for policy analysis when it takes into account context-specific (i.e. induced) technological progress. Rather than taking characteristics of existing and emerging technologies as given, their development should be considered as a function of dedicated R&D and market deployment under varying external conditions.

Energy systems analysis can assist R&D strategists in exploring R&D options. To provide such decision support insights, energy systems analysis tools must be equipped with mechanisms describing causality chains leading all the way from a certain R&D action to the impacts on targeted objectives. Such chains can be complex involving many interactions and certainly must address issues of technological spillovers, which can magnify impacts of R&D actions aimed at one technology but benefiting a number of others.

The above considerations have led to an increasing need to model the dynamics of technical change by incorporating appropriate mechanisms in detailed energy system models. In exploring the role of R&D and energy policy, the concept of learning or experience curve is employed, incorporating learning attributed to research effort and learning arising from the experience gained through technology take-up. The learning or experience curve reflects the fact that technologies may experience declining costs as a result of their increasing adoption due to the accumulation of knowledge through, among others, the processes of learning by doing and learning by research.

SAPIENTIA is an applied research project specifically aimed at analysing the mechanisms through which R&D actions translate into results in terms of specific objectives, and exploring R&D strategies in pursuit of such objectives. The project makes extensive utilisation of existing detailed models which describe the energy system in its considerable complexity and thus provides a consistent framework for the simulation of the impact of R&D actions. In addition to this aspect which utilises and extends modelling work that has been carried out over recent years the present project develops tools that synthesise these mechanisms while serving as compact vehicles for performing real R&D policy exploration exercises.

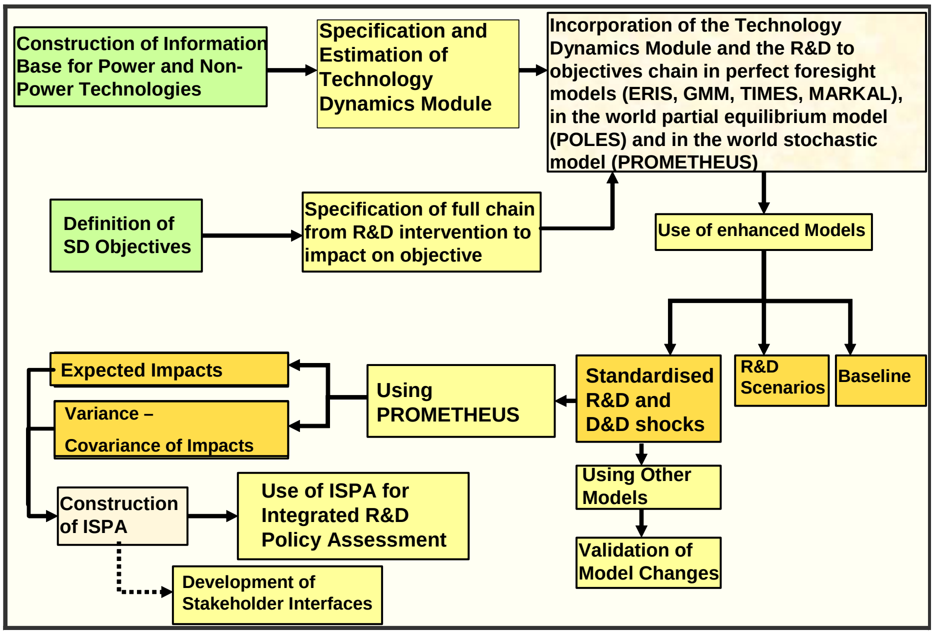
The methodology recognises two important characteristics of the R&D budgeting process. First that it evolves in a context of multiple objectives and second that it operates under uncertainty. Such uncertainty arises not only from the inability to predict the direct impact of R&D action but also from a host of other factors including uncertainty over parameters, key developments shaping the future economic conditions, future policy, political events and natural resource endowment. In order to support decisions an attempt was made to measure these uncertainties and incorporate them in a strategic analysis framework.

- Overall, SAPIENTIA has engaged in a series of ambitious scientific objectives, which constitute a clear advancement in the domain of energy systems analysis and modelling. These can be summarised as follows:
- Update existing data, collect new data and estimate numerical relationships that link technology improvement with investment and public and private R&D spending, particularly as regards non-power generating technologies, and describe more fully and operationally spillovers between technologies.
- Extend and refine a decision support tool that explores R&D priorities in a quest for minimising risks, hedging against uncertainty and maximising the economic, environmental and energy policy benefits from expected technological improvement.
- Extend the scope of existing large-scale energy system models so as to incorporate specific sustainable development indicators and integrate model results into the decision support tool.
- Extend deterministic and stochastic energy models to perform policy exploration exercises for the longer term (i.e. up to 2050).
- Address the issues of research versus demonstration in specific technologies.
- Consolidate into the operational versions of the large-scale energy models, past developments on the incorporation of endogenous (induced) technology improvement mechanisms.
- Co-ordinate the work from, and promote the synergies between, different energy models that differ in their methodology and the regional coverage.

SAPIENTIA is a very tightly designed project leading to very specific outcomes in the form of R&D policy exploration using the extended Integrating System for Priority Assessment (ISPA) tool involving proxy decision analysts. The work is organised around various sections covering distinct research needs contributing individually to the overall integration which was performed in the final stage of the project. The analysis draws from a very diversified set of areas of expertise involving information collection, statistical estimation, substantial model building and modelling extensions (to a considerable number of seemingly unrelated models incorporating different mechanisms and philosophies) that apart from serving the main objective of the project, have also provided useful insights on the dynamics of technical change in a period of increasing sustainability concerns.

The following table presents an overview of the methodology applied in the SAPIENTIA project:

Table 1-1 SAPIENTIA Project Overview



A major accomplishment of the project and prerequisite for all subsequent work has been the construction of an information base for power and non-power related technologies and the collection of technical-economic and R&D expenditure data for the specification and estimation of the technology dynamics module, which relates technological improvement to R&D and technology uptake. A set of measurable Sustainable Development (SD) objectives has been selected and analytical chains were specified leading all the way from a certain R&D action to the impact on SD objective. All models participating in SAPIENTIA (both deterministic and the stochastic model) were developed, re-specified and extended to incorporate the technology dynamics module. After some harmonisation of assumptions model generated baseline and R&D policy scenarios have been developed and compared. This has been essential in order to monitor and validate the model changes by all the modelling teams. The PROMETHEUS stochastic model provided the expected impacts and variance-covariance matrices of the impacts that were used in constructing ISPA, the policy integration tool used to perform Integrated R&D Policy Exploration.

The challenges faced to ensure the credibility of the whole process have been considerable throughout the project. The research agenda constituted from the very beginning a clear advancement in the domain of energy systems analysis and modelling. The following sections summarily report on all the above mentioned tasks undertaken within the SAPIENTIA project.

B. Information Base

I. Technology Characterisation and prospects

Markus Blesl and Michael Ohl **IER**

K.E.L. Smekens, G. Martinus and P. Lako **ECN**

1. Introduction

This report describes the outcome of the task in the SAPIENTIA project that was assigned to deal with the identification and characterisation of important non-power technologies. Unlike power technologies, which are characterised by a relatively homogeneous market and characteristics (power being a common end product), non-power technologies tend to be diffuse in character and have often attracted less attention in terms of characterisation and prospects. Yet they are crucial in terms of meeting R&D policy objectives.

Within this work package an extensive inventory of non-power technologies with good prospects for improvement has been compiled although the data were not as available as foreseen at the moment of design of the project. A selection is be retained on the grounds of their potential impact on future energy balances, their promise in terms of improvement, their interaction with other technologies including power generating technologies and the interest they have attracted in the recent past as candidates for R&D support both in the public and private sectors. The characteristics (and their variants) of the technologies retained are clearly laid out in order to serve among other things as a guide for the modelling work to be undertaken in other work packages.

The effort in performing and finishing this task was underestimated from the project design onwards and caused considerable delay in timing for the rest of the project.

From an initial long list, very soon a selection of technologies based on the data availability and their opportunity for the project had to be made. The focus remained on non-power technologies with a prospective wide area of application. The list was changed and reduced furthermore through the duration of the project, on the other hand request to include new options were also made by a project partner, but since the difficulties in finishing the work on the existing list of technologies, this request was turned down.

This report describes in detail the results of the extensive research concerning the short listed technologies. Chapters 2 till 5 deal with end use technologies in transport and in building environments (stationary fuel cells, heat pumps, condensing boilers); chapter 6 deals with a novel technology, the organic rankine cycle (ORC); chapter 7 treats CO_2 capture and storage (CCS) and finally chapters 8 and 9 deal with LNG liquefaction and electrolysis as mean for H_2 production.

Finally, an overview of the R&D expenditures for a number of specific technologies form the POLES database developed within this project is given. These technologies focus on the hydrogen energy chain, production and use. Also the methodology to set up an R&D time series from scarce and incomplete data is explained.

2. Automotive Technologies

The transport sector is a major contributor to the emission of greenhouse gasses (GHG). Thus, when extending the analysis of GHG reduction schemes to sectors other than the power sector, the transport sector is a prime candidate, in particular passenger transport. This holds even more if one considers the development of fuel cell technologies, and especially the spill over between applications of fuel cell technologies in the power sector and other sectors. Fuel cells are expected to play a substantial role in future developments in the transport sector, and the opportunities for such technologies are conditional on the development of competing technologies. Hence, it is imperative that one treats these competing technologies consistently.

The automotive industry is strongly centralised. Thus, efforts towards technological advances are concentrated in a few large companies, if not in actual work then at least financially. This simplifies the data collection, as one need only focus on a small number of firms. On the other hand, because the automotive industry acts in a highly competitive market, data is valuable. Many consulting companies aim at serving interested parties with specific data. What's more, economical data is specifically not considered to as public good, so whenever time series on this type of data is required, one can either purchase existing data sets, or go through the painstaking exercise of collecting the data anew. In the SAPIENTIA project, the first option was ruled out since the huge expenses involved. Therefore, we tried the second option.

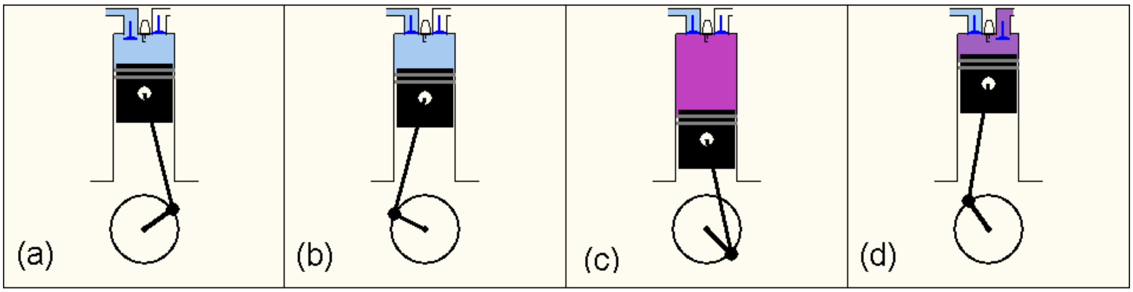
2.1. Technologies

The technologies under consideration are the Otto engine (internal combustion engine, or ICE, running on gasoline), the Diesel engine (ICE running on diesel), the electric engine using batteries and a fuel cell engine. Mixes between these may also be eligible for inclusion, but these will be considered as explicit hybrids. Of these options, only the Otto and Diesel engines can be considered as commercial options. The phases of the other two options can be described as demonstration (electric) and pilot (fuel cell), respectively.

2.1.1. Internal Combustion Engine

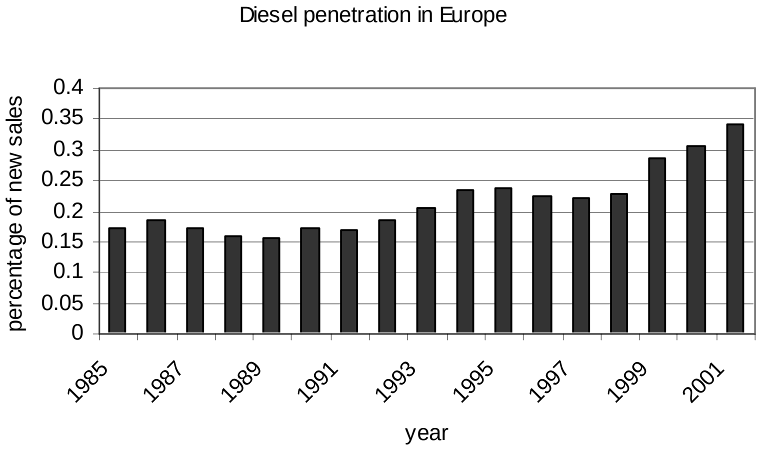
In automobiles, the most commonly applied concept of internal combustion engines is the four stroke engine (Wikepedia, 2004). In such an engine, a mixture of fuel and air is drawn into a cylinder through a first (downward) stroke of a piston. Next, the intake valve is closed, and the ensuing (upward) stroke compressed the fuel-air mixture. The mixture is ignited at (approximately) the top of the upward stroke, and the resulting expansion of burning gasses forced the piston down in a third stroke. In a final fourth stroke, the spent exhaust gas is exhausted through the then opened exhaust valve. The four-stroke process is illustrated in Figure 2-1.

<u>Figure 2-1: Cycle of a four-stroke engine: (a) intake of fuel and air, (b) compression of combustible mixture, (c) expansion after combustion, and (d) exhaust. Source: (Moros, 1998)</u>



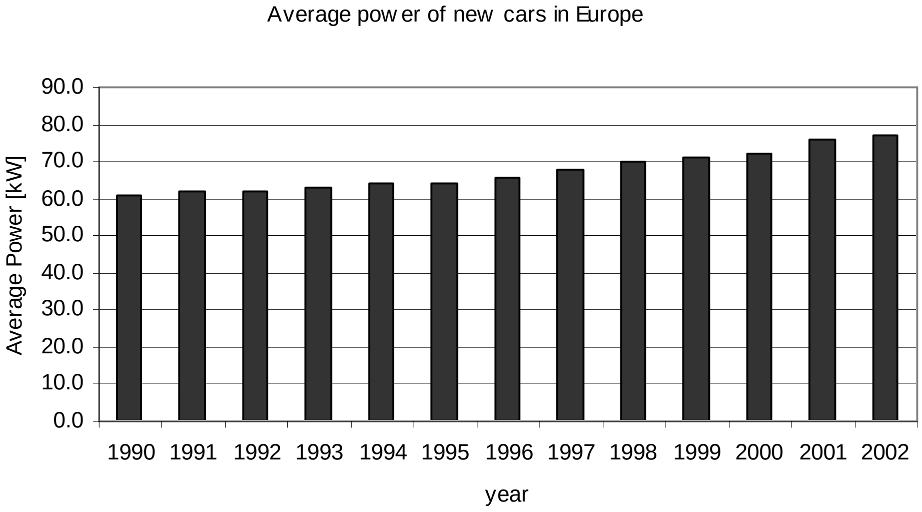
The development of the Otto engine has been a gradual ever since it became the dominant ICE type used in the automotive industry. At the same time, the diesel engine has developed in parallel to the development of the Otto engine. While the Diesel engine served mainly as a heavy-duty engine until the nineteen-seventies, from then on the market share of diesels started to increase world-wide, mainly as a result of the oil crises. In the United States this increase has been interrupted as the impact of the oil crisis slowly faded away. In contrast, the penetration of the diesel engine in Europe has seen extended growth, due to tax support schemes. This is illustrated in the figure below. In Japan, the diesel engine so far has not had a major share in personal transport. Thus, while the Otto engine remains the predominant engine type in the world as a whole, increased scarcity of fossil fuels in combination with an inherent higher efficiency of the Diesel engine may shift the balance in the years to come.

Figure 2-2: Diesel penetration in Europe measured by percentage of new sales. (Source: Odyssee)



Over the more than hundred years of its existence, the ICE in general has developed from a simple mechanical device to a complicated electronic system (Atzler, 2001). This development has led to considerable improvements in performance (Feirrera, 1998; Odyssee, 2004). However, as the rest of the automobile has also seen extensive changes, the improved performance has neither led to improved efficiencies (particularly in the previous ten years), nor to a decrease of costs for the car as a whole (in constant prices). Nevertheless, the improvement in cars, such as increased average power output of the engine, should actually be considered as implicit price decreases. In Figure 2-3 the development of average power in European new car sales is shown.

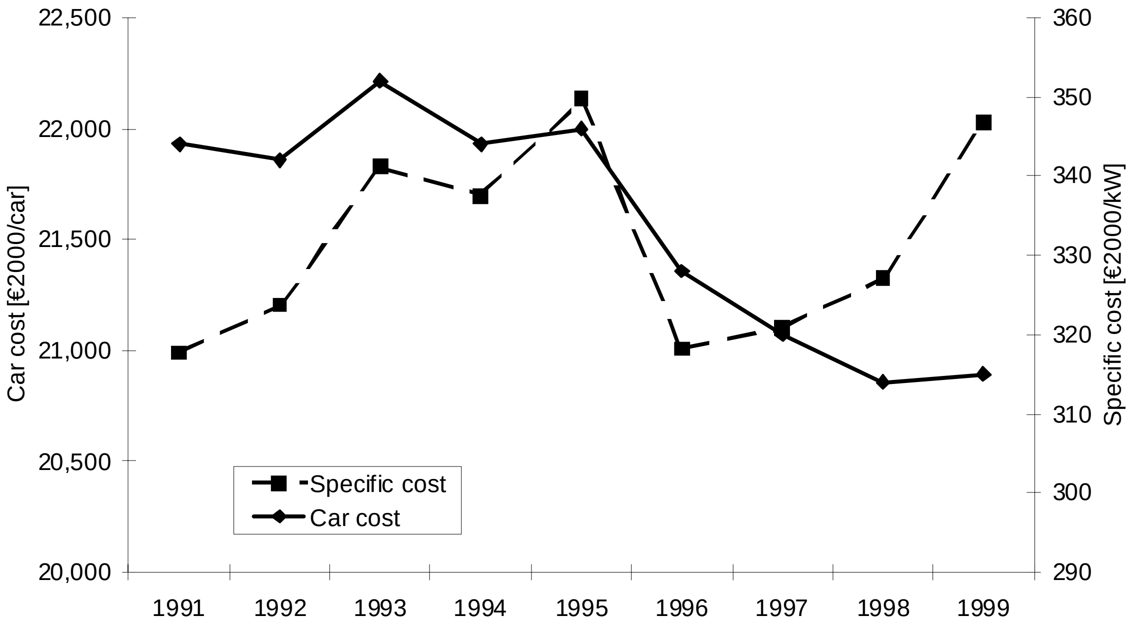
Figure 2-3: Average power of new passenger car registrations in Western Europe (EU+EFTA). Source: ACEA



2.2. Cost development for passenger cars

As mentioned above, the price of a passenger car has hardly seen improvements, measured on an absolute scale. This shown in Figure 2-4, where the cost development in the past decade is given for the average price of a new car is given, calculated as the turnover of the largest car companies divided by their sales. This shows a roughly constant value, of approximately €21,500 per car.

Figure 2-4: Passenger car cost, per car (left hand scale, in €2000/car) and per kW of engine output (right hand scale, in €2000/kW)



That the average price of a car would be the proper measure to assess future cost reduction potential is highly questionable, though. This is illustrated by second series shown in Figure 2-4, giving the average cost of new sales per kW. Here, a clear cost reduction can be seen, from some 350 €/kW to a little over 310 €/kW. The use of engine output power is used as a proxy for the capacity of the car, and the costs per kW are seen as specific costs of a car. Then, the trends in specific costs in principle can be analysed by comparing these to cumulative capacities[1].

Table 2-1 Parameters used in estimation of cumulative capacities and specific costs, global number summing or averaging over all types of cars

Parameter	Unit	Start	1991	1992	1993	1994	1995	1996	1997	1998	1999
Cumulative # cars	million cars		430441	452	463	474	485	496	508	521	534
Cost per car	€2000/car		20988	21205	21827	21697	22133	21007	21100	21327	22031
kW-price	€2000/(kW)		344	342	352	344	346	328	320	314	315
Power/car	kW		6162	62	63	64	64	66	68	70	71

2.3. Research and development in automotive technologies

Although other types of engines, and in particular also other types of fuels, have been available for quite some time, the major market share has been taken by the combination of gasoline and diesel cars. In some niche markets, small amounts of alternative fuels have been used (e.g. ethanol in

---

[1] Strictly speaking, the specific costs should be fitted to the cumulative installed capacity, which here would translate into sum of the product of number of cars sold per annum times the average engine capacity in that year. Unfortunately, there is insufficient data to do this.

Brazil, and LPG in the Netherlands) but on a world scale these have been negligible. Only in recent years, due to climate change concerns, alternative fuels have received increased attention. This is particularly clear from the R&D expenditures by companies, which can be deduced from the R&D budgets of companies combined with patent data. The patent data are shown in Figure 2-5 (absolute numbers) and Figure 2-6 (indexed numbers).

Figure 2-5: Number of patents for Otto engine (gasoline), diesel engine, Fuel cell and electric vehicle engine. Note the logarithmic scale. Source: esp@cenet

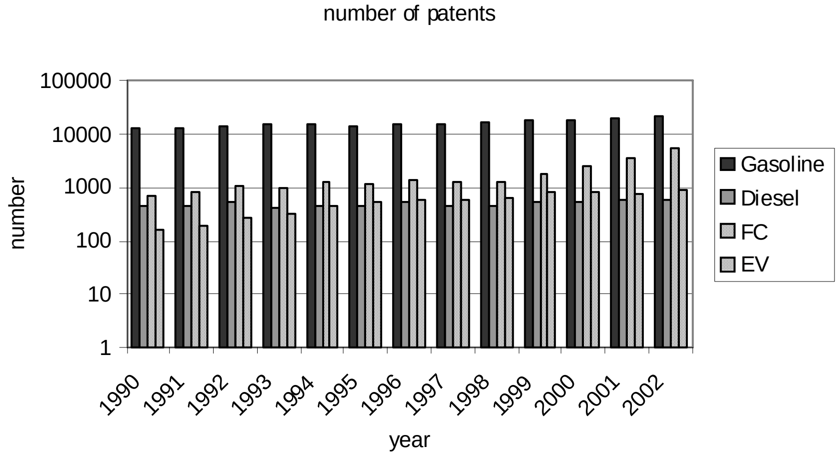
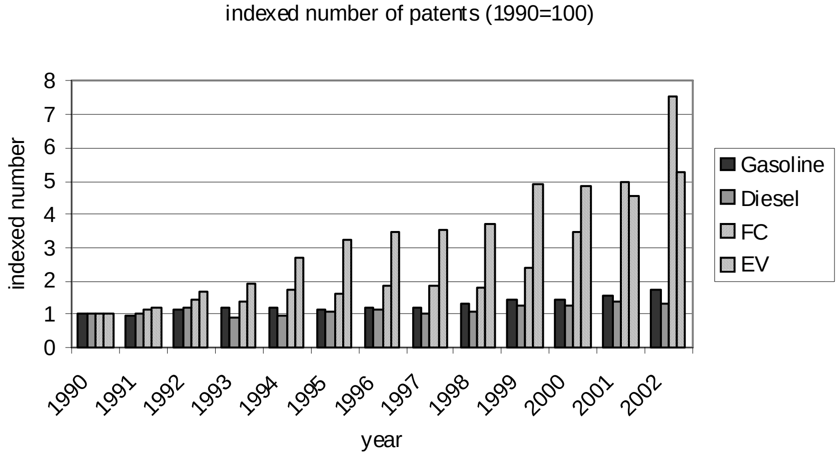


Figure 2-6: Indexed number of patents for various car types. Source: esp@acenet

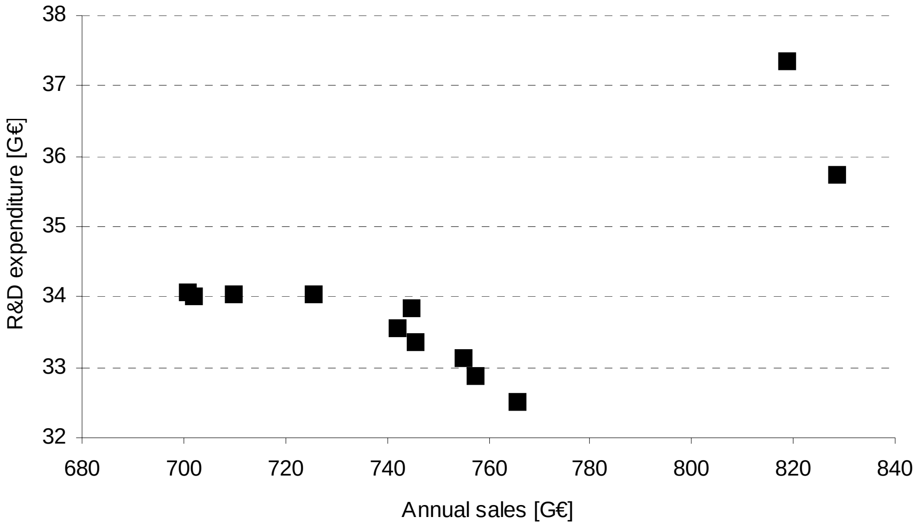


At present, dedicated electric vehicles are in a prototype stadium (Atlas, 2004; IEA-HEV, 2004). Japanese producers have focussed on the hybrid concept as a successfull means of introducing affordable (partial) electric drive automobiles, and have indeed managed to do so, as the introduction of the Toyota Prius (Toyota, 2004) and Honda Insight and Civic hybrid (Honda, 2004) have shown. Nevertheless, at the present production rate of a few tens of thousands per year world wide, a lot of effort needs to be put into further development of the electric vehicle.

The number of fuel cell cars at present is extremely limited, a total number quoted is around 100 (Atlas, 2004). This is partially due to the high price of fuel cell cars, which are far from commercial. Some car companies lease out fuel cell vehicles, but the lease price is not likely to be representative of the production costs. For example, is quoted to be of the order of 80,000 $US at present (Tsuchiya, Kobayashi, 2002) on the one hand, and a similar price only in ten years time (IHT, 2002). Introduction of fuel cells on a larger scale will require substantial political interference, in particular as ongoing developments in more conventional options complicate the market position of alternative fuels.

As mentioned above, R&D efforts are ongoing in all car types considered. This is reflected in the number of patents shown above, which can be used to disaggregate the R&D expenditures by car companies. The total budget is more or less a constant in the last decade, the estimate ranging between 33 billion € and 37 billion €. Plotted against the annual sales, we find a negative correlation. This is shown in Figure 2-7 where we show the research expenditures by major car manufacturers as a function of their sales. An actual fit would lead to a positive correlation, but the two higher values are clearly outliers.

Figure 2-7: Research expenditure of car manufacturers as a function of annual sales



The data given in these sections is incorporated in the R&D database which has been set up as a separate Excel file distributed to partners.

As data on the specific commitment of R&D expenditure by companies generally is considered as sensitive information, it is impossible to construct a database containing exact figures. In stead, one can try to deduce the expenditures by using an auxiliary variable (or proxy). In the present study, data on patents is used to disaggregate the R&D expenditures. Although for government spending (GERD) this does not necessarily hold, specific data is sparse, and an auxiliary variable may be used to improve estimates. The combined results of deducing Government R&D and business R&D expenditures are below.

Table 2-2: Estimated cumulative R&D expenditures by government and business

Year	Cumulative Government R&D (M€2000)				Cumulative Business R&D (M€2000)			
	Otto	Diesel	FC	EV	Otto	Diesel	FC	EV
1990					27,594	584	771	339
1991					31,225	648	919	451
1992					35,057	724	1,101	573
1993					39,039	774	1,255	734
1994	1,448	47		600	42,610	830	1,447	917
1995	1,575	50	541	776	45,656	890	1,608	1,104
1996	1,696	55	633	948	48,517	956	1,780	1,281
1997	1,810	58	710	1,112	51,195	1,008	1,933	1,454
1998	1,912	60	788	1,259	54,029	1,063	2,076	1,680
1999	2,015	64	896	1,405	57,133	1,131	2,296	1,886
2000	2,109	67	1,012	1,542	59,955	1,197	2,606	2,064
2001	2,206	70	1,143	1,682	62,868	1,270	3,008	2,264
2002	2,301	72	1,275		66,098	1,339	3,634	2,451

3. Stationary Fuel Cells

3.1. Market survey

On a global scale, an estimated 650 large stationary fuel cell systems (> 10 kW) had been produced and installed by September 2003 (Internet source 1). The average output of these systems is estimated at ~ 200 kWe. In the first half of 2002, the number of systems stood at 530 (Internet source 2).

Most of the stationary fuel cell systems installed today are Phosphoric Acid Fuel Cell (PAFC) systems (Internet source 3): around 260 units of the 200 kWe PC25™ PAFC system of UTC Fuel cells have been installed around the world since the system was launched in the early 1990s. The PAFC working temperature is about 200 °C. For PAFC systems, the allowable impurities in the fuel gas are: CO: 1%. Further limit values for different kinds of fuel cells are mentioned in Table 3-1.

Table 3-1: Fuel gas component limits for utilization in fuel cells [(1) Weindorf, Bünger, 1997; (2) mtu, 1999; USDOE, 2000)]

Substance	**PAFC**[1]	**MCFC**[2]	**SOFC**
sulphur	1 ppm	0,1 ppm	1 ppm
Chlorine	1 ppm	0,1 ppm	1 ppm
Fluorite	nda	0,01 ppm	nda
heavy metals	nda	0,1 ppm	nda
Particles	nda	1 µm	nda
excess pressure	nda	~ 200 mbar	nda
CO	1 %	fuel gas	fuel gas
Mercury	nda.	30-35 ppm	nda
N_2	4 %	nda.	nda
NH_3	0,2 ppm	1 vol.-%	nda
CH_3OH	500 ppm	nda	nda

nda: no data available

The largest PAFC system built was an 11 MWe system manufactured by Toshiba and UTC Fuel Cells (then known as International Fuel Cells). The cumulative installed capacity of stationary PAFC systems around October 2001 is estimated at approximately 75 MW (Table 3-2).

Table 3-2: Cumulative installed capacity and size distribution of PAFCs (estimate, 2001)

		50 kW$_e$	100 kW$_e$	200 kW$_e$	500 kW$_e$	1 MW$_e$ +	Total
Number		75	23	245	2	5	350
Capacity	[MW]	3.75	2.3	49	1	20	76

Also suitable for stationary applications is the Molten Carbonate Fuel Cell (MCFC, working temperature 650 °C). The smallest MCFC systems are rated at 250 kWe. During the last few years PAFC technology has been giving way to more prospective stationary fuel cell technologies: MCFC, Proton Exchange Membrane Fuel Cell (PEMFC, working temperature ~ 100 °C), and Solid Oxide Fuel Cell (SOFC, working temperature ~ 800 °C). In 2003, PAFC systems were outrun by MCFCs as the dominant type of fuel cell (in terms of numbers installed) (Figure 3-1).

Figure 3-1: Stationary fuel cells by technology type

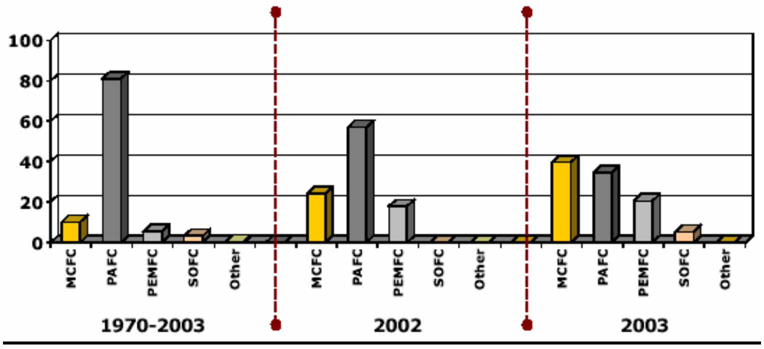
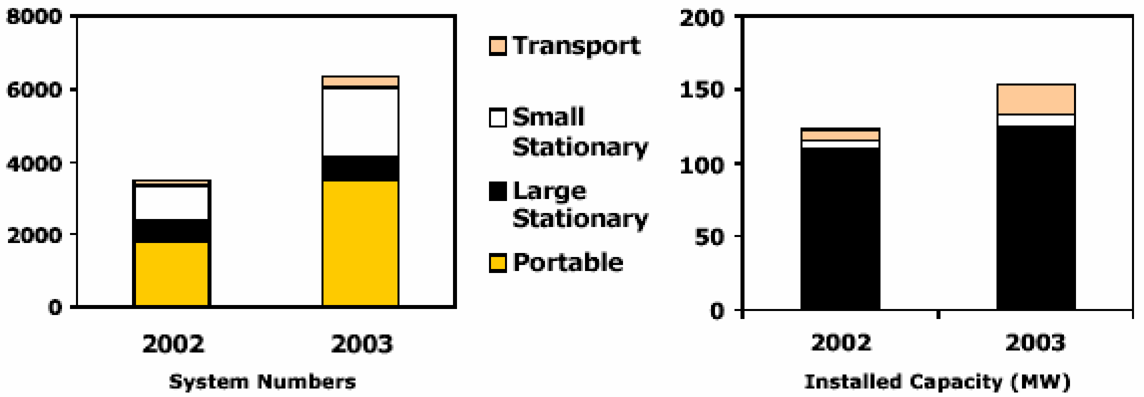


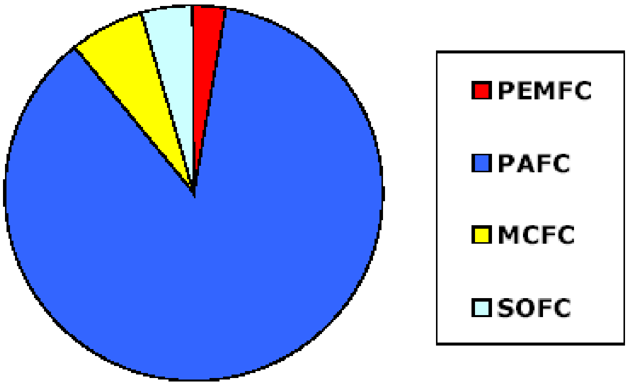
Figure 3-2 gives an indication of the cumulative capacity of (stationary) fuel cell systems installed by the end of 2002 and 2003.

Figure 3-2: Cumulative number and capacity of fuel cell systems by the end of 2002/2003



The capacity of large stationary fuel cell systems was about 110 MWe by the end of 2002. It is estimated that this capacity was approximately 130 MWe by the end of 2003. Figure 3-3 shows the distribution of fuel cell types among large stationary fuel cell systems by the end of 2001.

Figure 3-3: Distribution of technology types among large stationary fuel cell systems



It turns out that by the end of 2001 the leading technology – by percentage of systems installed – was PAFC (~ 83%), followed by MCFC (~ 8%), SOFC (~ 6%), and finally PEMFC (~ 3%).

Table 3-3 gives an estimate of the cumulative capacity and the cost of stationary fuel cells.

Table 3-3: Cumulative capacity and specific investment cost of stationary fuel cells (2003)

	Number (cumulative)	Capacity (cumulative) [MW_e]	Specific investment cost [€/kW_e]
PAFC	520	104	4,500-7,000
MCFC	70	10	6,000
SOFC	30	6	9,000
PEMFC	30	5	~ 12,000
Total	650	125	

Data for this table come from sources cited before, (Internet source 4), (Blesl, 2003) and (Manitoba, 2003). General Motors plans to install a 500 unit, 35 MWe fuel cell power plant at the Freeport industrial complex of Dow Chemical in the USA (The hydrogen & fuel cell letter T, 2003). This power plant will use automotive fuel cell stacks, if the test phase of the project will prove successful. The size of (automotive) PEM fuel cell units is approximately 70 kWe.

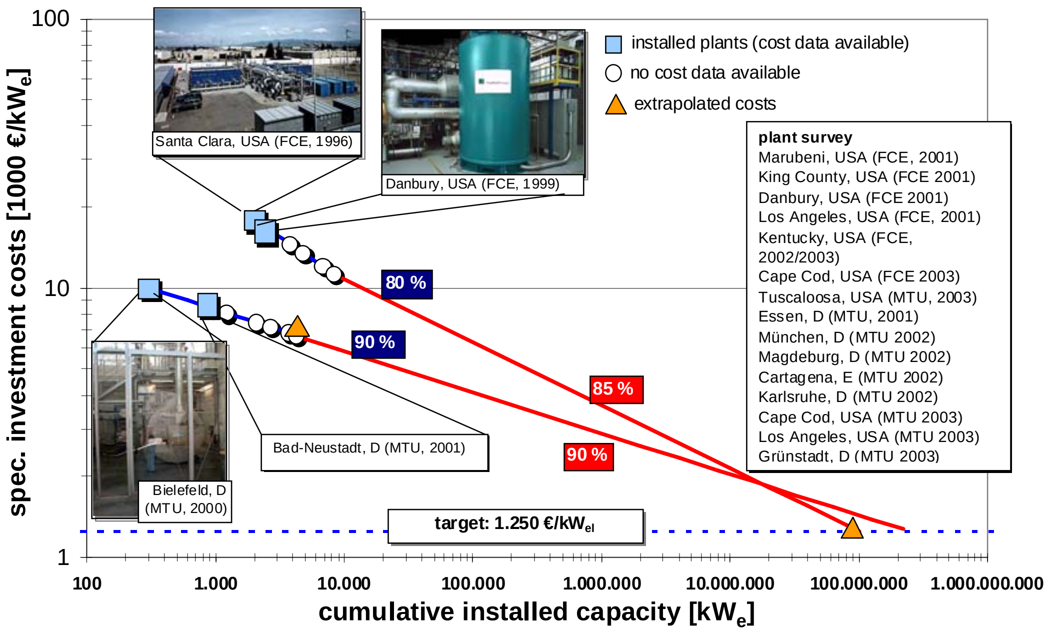
The US Department of Energy (DoE, 2003) has the following view on stationary FCs:

"Over the last several years, phosphoric acid, tubular SOFC, and MCFC systems > 200 kW have been demonstrated at costs of $4,000-12,000 per kW. As further R&D improves cost and reliability, Federal and State governments can team with private industry to share risks and costs of limited prototype tests. Cost reduction and technology improvement managed by partnerships are critical in the current phase of technology development. Only technologies that have the potential to approach an installed cost target of $400/kW would be pursued through further RD&D. This cost target is based on 5 kW modular systems at a production volume of 100,000 units".

3.2. Learning curve examinations for MCFC and SOFC

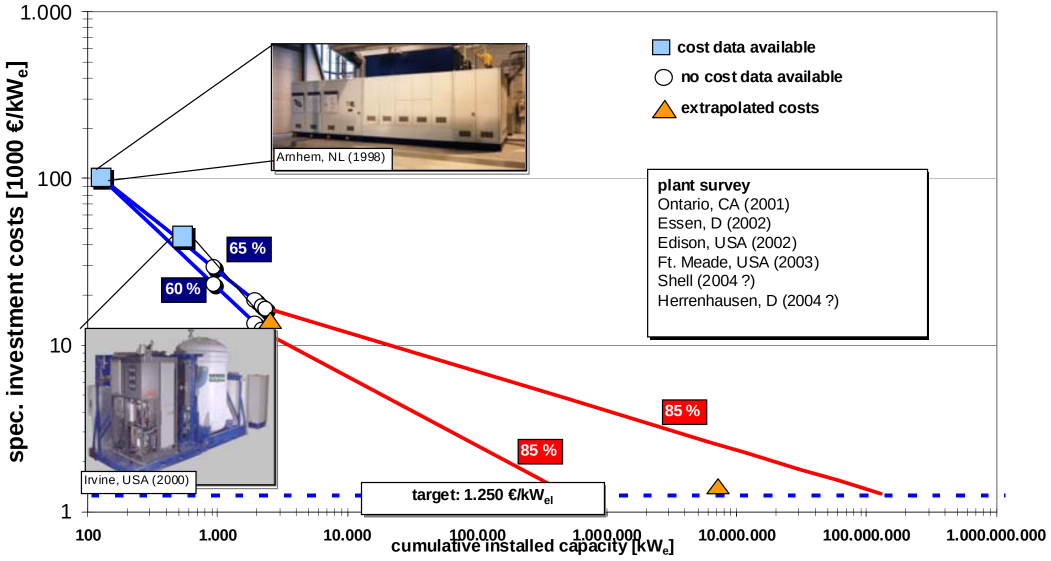
Target investment costs for high temperature fuel cell systems in the 200-2000 kWe range in order to prevail in the market are 1200-1500 €/kWe. Figure 3-4 and Figure 3-5 give information about the cumulative capacities required to reach investment cost targets for assumed learning rates of MCFCs and SOFCs. Whereas for demonstration plants learning rates are 0,6-0,65, the impact of learning after market entry is expected to shrink. Then for MCFC systems learning rates are assumed to be 0,85 respectively 0,9. These learning rates require cumulative capacities of 100 GWe respectively 250 GWe to reach the cost target.

Figure 3-4: Learning curve for MCFC systemsin the USA and in Europe (Blesl et al., 2004)



For SOFC systems a future learning rate of 0,85 was assumed. With this learning rate a cumulative capacity of 35-130 GWe is necessary to meet the target investment costs.

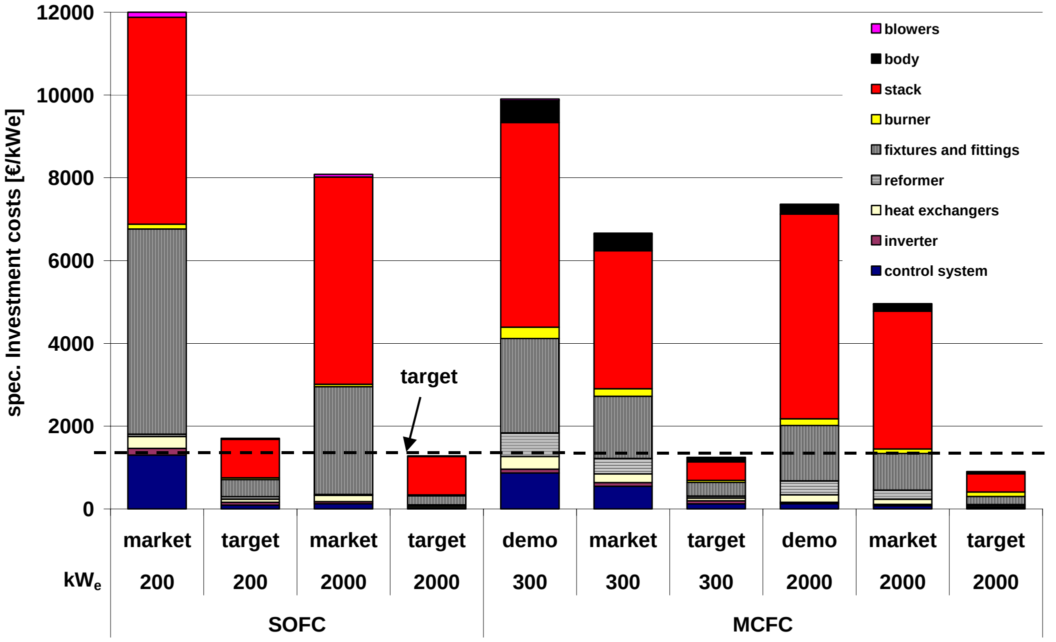
Figure 3-5: Learning curve for SOFC systems (Blesl et al., 2004)



Anyhow, there may be limitations to the learning curve approach like excessive public subsidizing or the customers´ willingness to accept high prices. Both factors keep investment costs on a high level despite considerable rises in cumulative production, as seen in the field of wind power generation (Blesl et al., 2004).

Besides the learning effect by growing cumulative capacities, the effects of scale-up are considered. Therefore the MCFC and SOFCs are fractionalised into their components. As most of the components of high temperature fuel cells, e. g. pumps, heat exchangers, or inverters, have also been applied in other, established technologies, mass production of these parts has already been existing. So the investment costs for conventional application can be taken as bottom-line costs of these components. Only a few components of fuel cells, like the stack, are only used for fuel cell application. For these components no target costs can be derived from any application in other technologies.

Figure 3-6: Influence of learning on specific costs of MCFCs and SOFCs (Blesl et al., 2004)

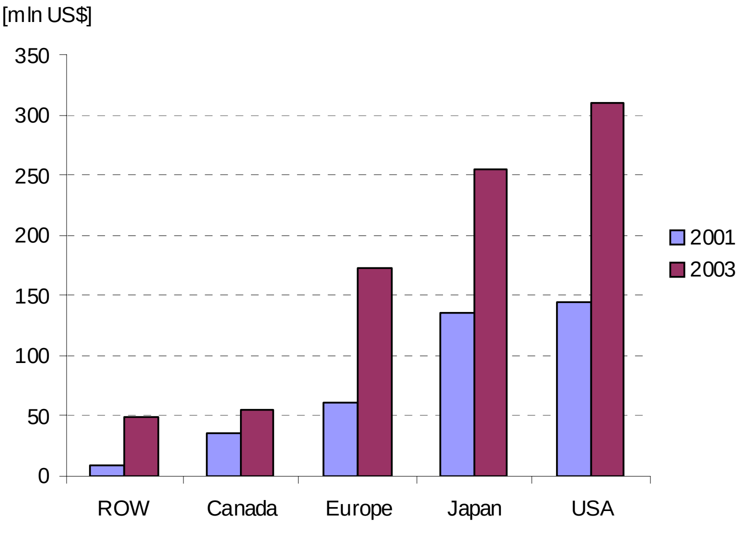


With the overall investment costs of different development stages allocated to the single components for different capacities of high temperature fuel cell systems MCFC and SOFC, IER (Blesl, 2003) presents specific cost targets in the range of 962-1,712 €/kWe (Figure 3-6). It turns out that for some plant capacities, esp. the smaller ones, target costs can not be reached without further progress in the process scheme. So, for example, the reformation unit might be replaced by producing the hydrogen inside the MEA.

3.3. Public R&D expenditures

Figure 3-7 presents an overview of public R&D expenditures on fuel cells in world regions (The Clean Fuels and Electric Vehicles Report, 2003a).

Figure 3-7: Public R&D expenditures on fuel cells (2001 and 2003 *[The Clean Fuels and Electric Vehicles Report, 2003a;* ***Http://www.fuelcelltoday.com****]*



For the U.S. detailed data is available for the years 1996-2002, with a distinction between public and private R&D expenditures (Internet source 5) (Figure 3-8 and Figure 3-9).

Figure 3-8: Public and private fuel cell R&D expenditures in the USA

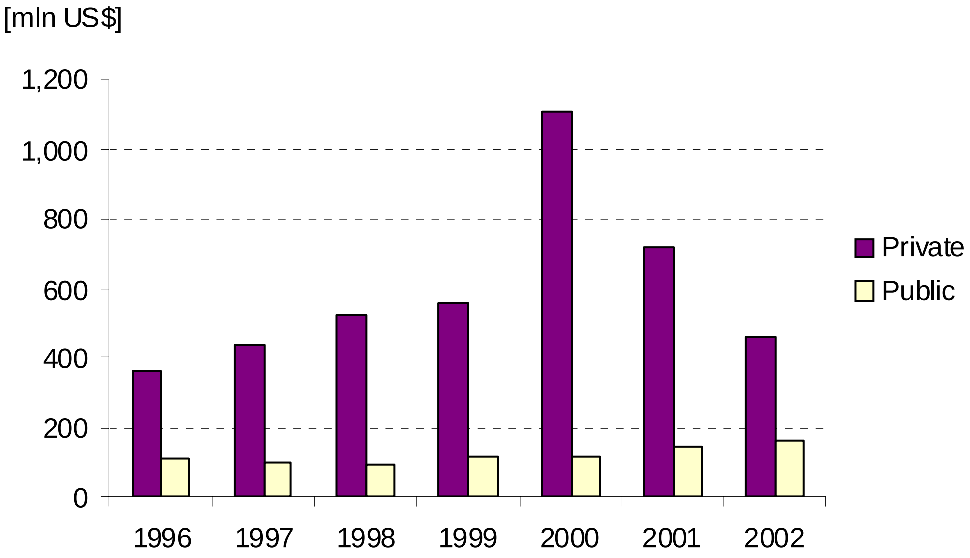
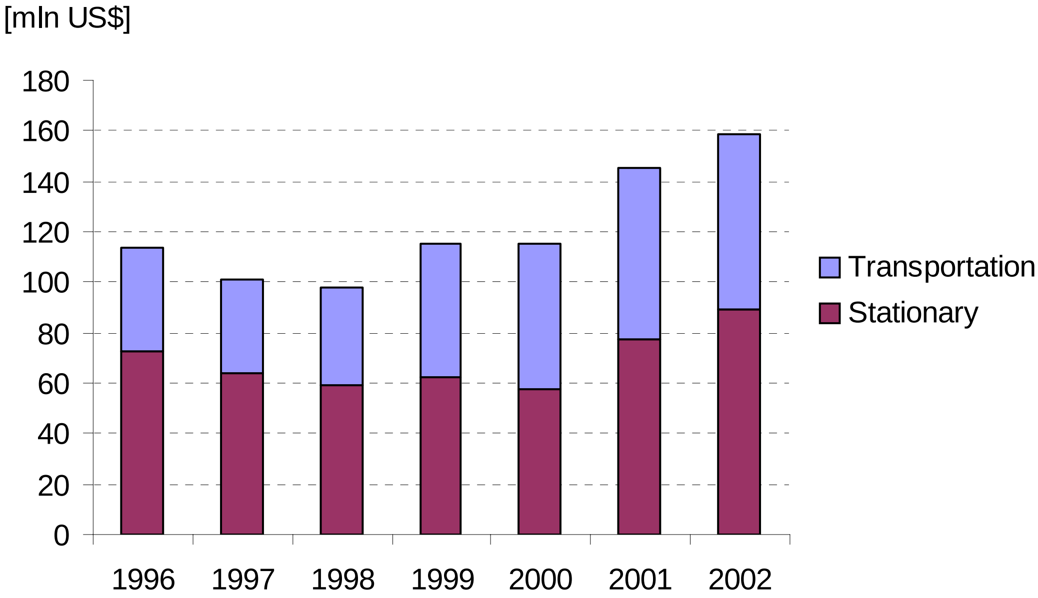


Figure 3-9: U.S. federal fuel cell R&D expenditures by market



According to the 'Breakthrough Technologies Institute', federal R&D expenditures on fuel cells rose from $114 mln in 1996 to $159 mln in 2002. Federal expenditures on stationary fuel cell R&D showed a 'dip', whereas expenditures on transportation fuel cell R&D rose steadily.

Private sector R&D expenditures of in the US were much less stable, and showed a peak of some $1.1 billion in 2000 (Figure 3-8). These private R&D expenditures have not been disaggregated into stationary fuel cell R&D and transportation fuel cell R&D. In 2001, Europe's industry invested some $120 mln in joint fuel cell R&D programs with governments.

4. Capture and Sequestration of Carbon Dioxide

Carbon dioxide capture and sequestration (CCS) has gained a lot of interest lately, not only in the context of climate change, where it may be used to mitigate the effects of CO_2 emissions, but also from industry, as it provides a motive for extension of lifetime of coal power plants in the USA. While it is regarded as a new technology in the context of energy systems, in the chemical industry CO_2 separation already occurs for process purposes. However, as industry and material flows fall outside the scope of this study, the industrial use of CO_2 separation will not be treated, and hence the focus will be on energy related CO_2 capture. Furthermore, the use of natural occurring CO_2 for enhanced oil recovery and the single example where it is used for enhanced coal bed methane recovery will not be considered here.

4.1. Current status of CCS

The development of CCS is mostly in the research and development phase, with only three demonstration projects in progress. Presently, only tree sites are actually capturing and storing the captured CO_2. In Norway, CO_2 is captured from gas mined at the Sleipner oil field, and sequestrated instead of vented to the atmosphere. At the Weyburn facility in Canada CO_2 from a coal gasification plant in the USA is used in enhanced oil recovery. Further projects with CO_2 capture from energy processes are announced but are only on the drawing board at this time, such as capture and storage at LNG facility in Australia.

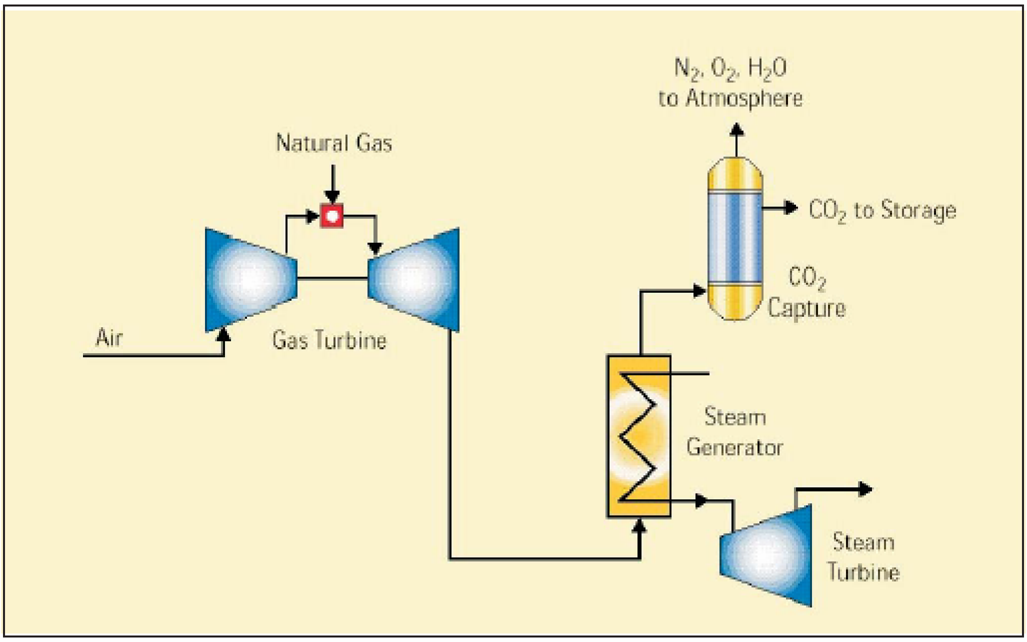
4.2. Technologies

The IEA GHG R&D programme has collected a extensive number reports containing thorough descriptions of technologies, with all possibilities and parameters. For detailed technology analysis and comparison these are very valuable, but for large energy system analysis tools, they prove to be too detailed. For this study, two technology options for capture will be retained. They cover the bulk of the capture possibilities and have a wide area of application that is favourable for technology spill over effects.

4.2.1. Post combustion separation and capture of CO_2

A variety of techniques is available for post-combustion separation of CO_2 from the flue gas. The main one in use today is scrubbing the gas stream using an amine solution. After leaving the scrubber, the amine is heated to release high purity CO_2 and the CO_2-free amine is then reused. This option can also be used for separation of CO_2 from other gas streams. As an example of the process, Figure 4-1 shows the capture from a natural gas turbine.

Figure 4-1: Post-combustion capture of CO_2, here shown for capture from a gas turbine



In many respects, post-combustion capture of CO_2 is analogous to flue gas desulphurisation (FGD), which is widely used on coal- and oil-fired power stations to reduce emissions of SO2. The flue gas has low concentrations of CO_2, ranging from 14% in pulverised coal (PC) power plants, through 9% for integrated gasification combined cycle (IGCC) power plants, to as low as 4% in natural gas combined cycle (NGCC) power plants. This leads to large volumes of gas that have to be handled, resulting in large and expensive equipment. A further disadvantage of the low CO_2 concentration is that powerful solvents have to be used to capture CO_2. Consequently the regeneration of these solvents in order to release the CO_2 requires a large amount of energy. The CO_2 capture rate presently is about 85%, and is expected to increase to 90 % in 2010, i.e. 85% of the carbon contained in the flue gases (and hence in the fuel) is separated and ready for storage, the remaining 15% is vented in the air.

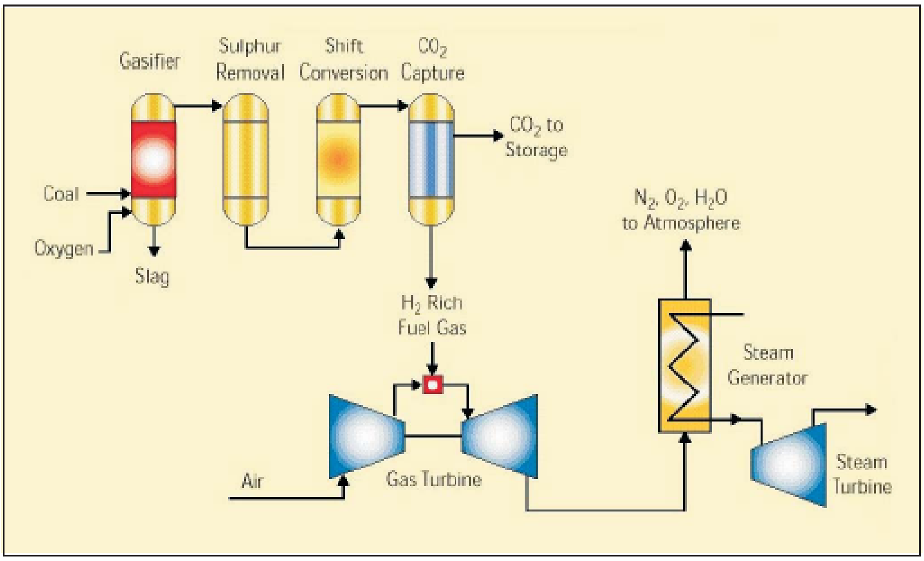
CO_2 concentration can be increased greatly by using concentrated oxygen instead of air for combustion, either in a boiler or gas turbine. If fuel is burnt in pure oxygen, the flame temperature is excessively high, so some CO_2-rich flue gas would be recycled to the combustor to make the flame temperature similar to that in a normal combustor. The advantage of oxygen-blown combustion is that the flue gas typically has a CO_2 concentration of over 90%, so only simple CO_2 purification is required. The disadvantage is that production of oxygen is expensive, both in terms of capital cost and energy consumption. This option is actually not considered due to lack of information about dedicated oxygen technologies (turbines, combustion chambers) for power technologies.

The post combustion option is considered to be suitable for CO_2 capture from all flue gas flows from power plants (and large industrial boilers). As mentioned above, it is even suitable for other processes involving the separation of CO_2 from gas streams; e.g. the Sleipner project uses the same technology with amine scrubbers to remove excess CO_2 form the extracted natural gas.

4.2.2. Pre-combustion capture of CO_2

An alternative way to increase the CO_2 concentration and partial pressure is to use pre-combustion capture. This involves reacting the fuel with oxygen and/or steam to give mainly carbon monoxide and hydrogen. The carbon monoxide is reacted with steam in a catalytic reactor, called a shift converter, to give CO_2 and more hydrogen. The CO_2 is then separated, e.g. using Selexol as solvent and with depressurisation to release the CO_2. The hydrogen is used as fuel in a gas turbine combined cycle plant. In principle, the process is the same for coal, oil or natural gas. In Figure 4-2 a simplified diagram of a coal-fired (IGCC) power plant with pre-combustion capture of CO_2.

Figure 4-2: Pre-combustion of CO_2 , here shown for an integrated gasification combined cycle process



Although pre-combustion capture involves a more radical change to the design of the power plant, most of the technology is already well proven in ammonia production and other industrial processes. One of the novel aspects is that the fuel gas is essentially hydrogen. Although it is expected that it will be possible to burn hydrogen in an existing gas turbine with little modification, this is not a commercially proven technology. Nevertheless, at least two gas turbine manufacturers are known to have undertaken tests on combustion of hydrogen-rich fuels.

The hydrogen produced in pre-combustion capture processes could, alternatively, be used to generate electricity in a fuel cell. The technology of capture and storage is therefore expected to be suitable for future as well as current power generation technologies, and may even prove to be useful in a transition towards an energy system without fossil fuels.

Pre-combustion capture can be considered suitable for all fuel treatment processes in which hydrocarbons are shifted to H_2 and CO_2. Thus it can play a role fossil fuel gasification for electricity generation as well as in H_2 production from the (partial) oxidation of natural gas, oil or solid fuels (coal and biomass). The capture rate presently lies above 90%, and is can reach 97% for H_2 production facilities. The Weyburn facility uses CO_2 from a synthetic fuel plant, in thus is an example of a pre-combustion separation and capture process.

4.3. Characteristics of CO_2 capture technologies

4.3.1. Costs of CO_2 capture

The costs of carbon capture are usually expressed as additional costs, rather than in terms of absolute costs. For post-combustion CO_2 capture, these additional costs are expected to decrease roughly one third between now and 2012 (Herzog, 1999,2003; David, 2003). For the long term, an assumption on the floor costs can be made, which will still depend on the type process used as well as on the fuel used. The actual costs for the various technologies are summarized in Table 4-1, which however does not include the option of retrofitting existing coal-fired plants. It is expected hat retrofitting can be done at additional cost of 710 US$/kWelectric.

Table 4-1: Additional cost of CO_2 capture for pre- and post combustion capture (Herzog, 1999, 2003)

Process	2000 [US$/kWe]	2003 [US$/kWe]	2012 [US$/kWe]	floor cost [US$/kWe]
pre combustion capture		451-504	314	180
post combustion coal	920	890	623	400
post combustion gas	470	370	314	200

4.3.2. Energy penalty of CO_2 capture

The capture of CO_2 from an electricity producing process will result in a loss of efficiency, which is called the energy penalty. Thus, the energy penalty of CO_2 capture is the difference in efficiency between similar power plants without and with CO_2 capture. It is largest for post-combustion processes, where it currently lays around ten percent for coal fired power plants, and slightly less for gas fired power plants. These energy penalties are expected to decrease due to further optimization of the components in the CO_2 capture process, to six percent by 2010. For pre-combustion capture the energy penalty is expected to decrease from its present level of a little over six percent to some four percent in 2012. All in all, one might say that the energy penalty is expected to be rather small as compared to the power plant efficiencies. A summary of the numerical values is given in Table 4-2.

Table 4-2: Energy penalty of CO_2 capture

Process	2000 [%]	2012 [%]
pre combustion capture	6.1	4.3
post combustion coal	10.2	6.0
post combustion gas	7.2	6.0

4.3.3. Additional costs of CO_2 capture from H_2 production

Another technological option in which capture of CO_2 may occur is in the production of H_2 by means of partial coal oxidation processes. For such processes, additional costs for CO_2 capture ranges from 2.2 to 2.9 US$2000/(GJ H_2).

4.4. Storage options

Capturing of CO_2 is not sufficient to remove it from the atmosphere, a safe and permanent storage is also required. To store CO_2 again different options are recognized. The most important ones are to be found in geological storage. Storage in mineral products or for example in use in food products (gasified drinks), or other more ‘exotic’ forms of sequestration are not expected to contribute significantly to climate mitigation. Particularly because it is hard to imagine how such options could be comparable in scale with respect to the quantities of CO_2 capture from energy technologies. Sequestration in biological sinks, such as forest and soils, is not considered here because these options capture the CO_2 directly from the atmosphere and do not need a separate capture technology or process.

There are various options that can be used for geological storage of CO_2. Here, the following are considered:

- Depleted oil and gas fields: the CO_2 is injected into fields that have been taken out of production,
- Enhanced oil and gas recuperation (EOR and EGR): the CO_2 is used as a means of pressurizing a production field, thus combining the advantage of CO_2 storage with the benefits of continued mining,
- Unminable coal seams, combined with the recovery of methane (generally referred to as enhanced coal bed methane, ECBM). Like in the previous option, this storage option has a side benefit, in that the storage results in the recovery of methane
- Saline aquifers: storage in underground saline water reservoirs.

The option to store the CO_2 in oceans is expressively not included. At present, its impact on the environmental is unclear, making it highly unsure whether this particular option is acceptable in the long run. Such misgivings do not (to the same extend) exist for the other options.

4.4.1. Potentials of storage options

The various options each come with their own global potential. These are summarized in Table 4-3, where the potentials according to two different sources are given. The potential as given by (IEA, 2001) is expressed in terms of the cumulative storage capacity up until 2050, whereas (Edmonds, 2000) provides an estimate for the total cumulative capacity. The table clearly illustrated that the most important option is the storage in saline aquifers, as this is the most abundant resource.

Table 4-3: Potentials for CO_2 storage according to (IEA, 2001) and (Edmonds, 2000), respectively.

	Gton CO_2 2050, (IEA GHG, 2001)	Gton CO_2 (Edmonds , 2000)
Depleted oil fields	126-400 oil	150-700
Depleted gas fields	800	500-1100
Enhanced oil recovery	61-65	
Unminable coal seams	>15	>73
Saline aquifers	400-10 000	320-10 000

There are some studies reporting on regional distributions for some of the options. These are included in the Annex. One of these studies also provides estimates for technical and economical parameters. Furthermore, it gives an overview of the operations currently taking place. These are mainly concentrated in the USA, where the oldest project in the world is running, in which 33 Mton CO_2 per year from natural resources has been stored in enhanced oil recovery since 1972. Since 2000, use of CO_2 sequestration in enhanced oil recovery at the Weyburn field resulted in an annual storage of 1 Mton CO_2. A further 30 kton per year from natural sources has been stored in the USA in enhanced coal bed methane mining. Presently, the only long-running project outside the USA is the injection of removed CO_2 into saline aquifers at the Sleipnir field, in the Norwegian part of the North Sea.

4.4.2. Costs of storage options

It is clear that the range in the estimates of potentials is considerable. Therefore, it should come as no surprise that the cost estimates are far from uniform. Moreover, in many cost estimates for storage in combination with enhanced recovery, the price of oil or gas is included in storage cost estimates. The uncertainty, and in some cases model-dependence of these prices, make it hard to directly use the cost estimates, while at the same time the present price range make a de-convolution far from trivial. As it is often unclear what assumptions have been used , making it difficult to use, especially because of the uncertainty and range of these fuel prices. When the fuel costs are included, quite often negative storage costs per ton CO_2 are quoted, taking into account the benefits from the energy recovered (oil, gas or coal bed methane).

Nevertheless, some order-of-magnitude estimate for the costs of storage can be obtained from the literature. The estimates are given in Table 4-4, together with some technological characteristics, such as the amount of electricity needed per ton of CO_2. For those options where the CO_2 is applied in the extraction of fossils, also the energy recovered per ton CO_2 is given.

Table 4-4: Economical and technical parameters for various storage options according to (Smekens, 2003; IEA, 2004)

	Depleted fields	EOR/EGR	ECBM	Aquifers
Investment cost [US$/ton CO_2]	5-11	5-11	12.5-17.5	1-11
Transport cost [US$/ton CO_2/300km]	2.5	2.5	2.5	2.5
Fixed O&M cost [US$/ton CO_2]	0.25-0.35	0.17	0.25-0.50	0.375
Variable O&M cost [US$/ton CO_2]	1.35	0.90	12.5	0.30
Electricity requirement [MWh/ton CO_2]	0.08-0.11	0.14	0.08-0.21	0.11
Energy recovery [GJ/ton CO_2]	-	1.80-2.22	5.5-9.0	-

4.5. Cumulative capacity for capture and storage

In Table 4-5 the cumulative capacity of CO_2 capture and storage is given, including the capture from natural resources, but with the exception of the 33 Mton CO_2 per year in EOR in the USA

In the USA there is experience over a couple of decades already about CO_2 storage in enhanced oil recovery (EOR), but this is not driven from a climate point of view but purely business driven in order to increase oil production. This actually has consequences for the storage time - it is uncertain in many cases whether CO_2 storage is actually taking place. In this context it is justified to rather use "CO_2 injection" in stead of "CO_2 storage" for the present the US EOR activities.

In addition, leakage and accounting play now no role in the existing CO_2 storage in EOR in the USA. About retention times and leakage rates to the atmosphere, some studies are available, but they are not supported by empirical data. There is also no risk assessment methodology and the EOR projects usually take place in sparsely populated areas, so no problem with public resistance.

Furthermore, most EOR projects use CO_2 from natural sources (the purchase of which contributes on average to 68% of the storage costs) and therefore do not mitigate climate change (Johns et al , 2002).

Table 4-5: Cumulative capacity for CO_2 capture and storage in Mton CO_2 per year

	1995	1996	1997	1998	1999	2000	2001	2002	2003
Capture		0.2	1.2	2.2	3.2	4.2	6.2	8.2	10.2
Stored[1)]		0.2	1.2	2.23	3.26	4.29	6.32	8.35	10.38

1) Excluding 33 Mton per year from enhanced oil recovery in the USA

In the Sleipner project, CO_2 is captured in the exploitation of a gas field. The CO_2 is separate from natural gas through scrubbing, and as was explained in paragraph 7.2.1, this process may well be compared to post-combustion capture of CO_2 in a power plant. The resulting CO_2 from the Sleipner field is stored in a saline aquifer. The process is active since 1996 at a rate of 1 Mton CO_2 per year, with a smaller amount in the year of start-up. As can be seen from the table, the other contribution to the cumulative capacity in carbon capture starts up in 2000, as the Weyburn facilities starts to contribute another 1 Mton CO_2 per year. Here, the capture is done in a shift reactor (i.e. in a gasification plant), and the CO_2 is used in EOR. Two smaller contributions, to storage only, are the 30 kton per year since 1998 from the Allison unit in the USA, and a further 2.2 kton stored in aquifers in Japan from 2003 onwards.

It is clear that there is only very limited experience with an integrated system involving capture of CO_2 and its storage. Strickly speaking, there is only one project in which CO_2 is actually captured in a power plant, namely at the Weyburn facility. However, because of the similarities between separating and capturing CO_2 from natural gas, the data from the Sleipner project can be included under post combustion capture. Thus, the capacities associated to the Weyburn and Sleipner projects can be estimated using the capture amount of CO_2, in combination with an estimated efficiency and operation conditions. The resulting numbers are given in Table 4-6.

Table 4-6: Cumulative capture capacities for key technologies in the power sector in MWe

	Region	1995	1996	1997	1998	1999	2000	2001	2002	2003
post combustion gas	Western Europe	0	70	350	350	350	350	350	350	350
pre combustion	USA						0	210	210	210

4.6. R&D expenditures

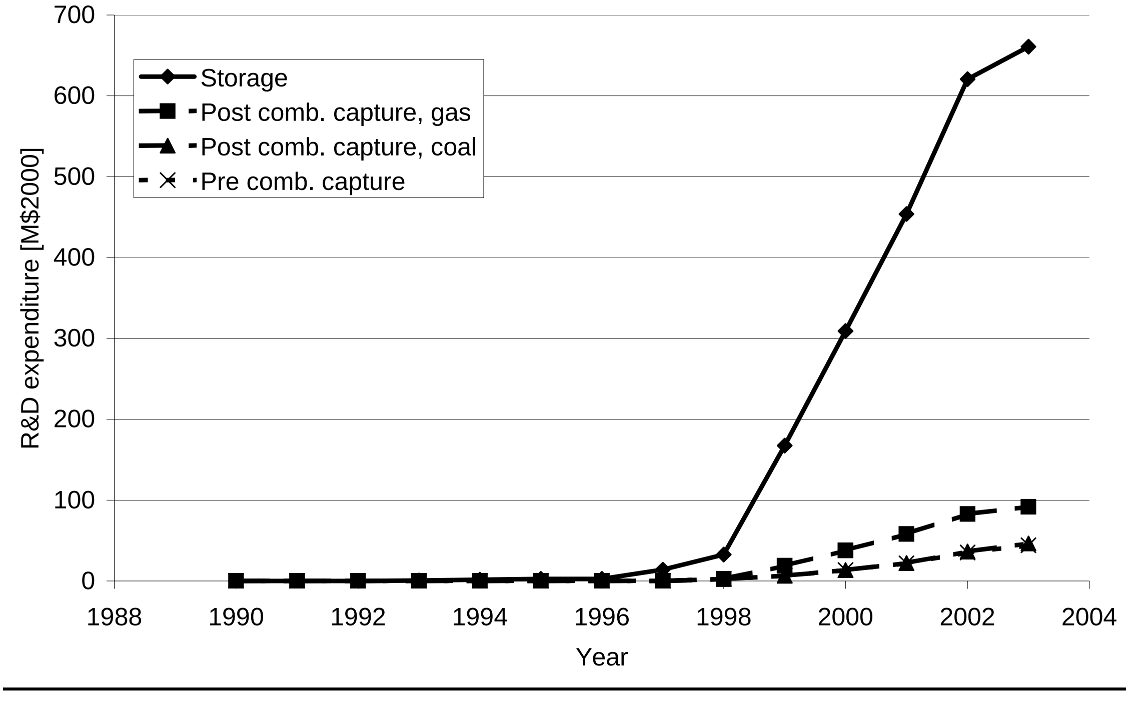
Various sources are available from which estimates of R&D expenditures can be constructed. As the major part of the interest in CCS technologies stems from the previous decade, and the interest is furthermore concentrated in a few projects, data on the major projects seems to suffice for such an estimate. An overview is provided in Table 4-7. In case a project concerns both capture and storage, it is assumed the expenditures are shared equally between these two technologies.

Table 4-7: Estimated cumulative R&D expenditures in M€2000 (comb. stands for combustion)

Year	Capture			Storage
	Pre comb.	Post comb., coal	Post comb., gas	
1990	0	0	0	0
1991	0	0	0	0
1992	0	0	0	0
1993	0	0	0	0.8
1994	0	0	0	1.7
1995	0	0	0	2.5
1996	0	0	0	2.5
1997	0	0	0	13.9
1998	2.5	2.5	2.5	32.7
1999	6.5	6.5	18.8	167.5
2000	13.5	13.5	37.8	309.2
2001	22	22.1	58.2	453.9
2002	35.3	36.5	82.8	620.6
2003	44.1	46.5	91.7	660.7

A graphical representation is provided in Figure 4-3, showing clearly that energy related R&D for CO_2 capture and storage has only gained interest the last decade or so. Furthermore, storage is currently clearly the main field of interest from the point of view of R&D.

Figure 4-3: Estimate for energy related R&D expenditures on capture and storage of CO_2



5. Hydrogen Production Technologies

5.1. Electrolysis

5.1.1. Technology description

In this report only electrolysis as mean for hydrogen production is considered. The main feedstock is water which is converted to H_2 and O_2 by means of electricity.

Electrolysis accounts for 4% of the global hydrogen production (Duwe, 2003) (Table 5-1).

Table 5-1: Current global hydrogen production

Origin	Amount of hydrogen	Fraction
	[billion Nm^3/a]	[%]
Natural gas	240	48
Oil	150	30
Coal	90	18
Electrolysis	20	4
Total	500	100

The following industries supply electrolysers (Internet source 6):

- GL&V Hydrogen Technologies, Montreal.
- Hydrogen Systems N.V., Belgium.
    - Norsk Hydro, Norway.
    - Proton Energy Systems, Inc.
    - Stuart Energy Systems, US.
    - Tathacus Resources Ltd.
    - Teledyne Energy Systems,
    - Waterflame, Thailand.

5.1.2. Cost development

Basically, there are three types of electrolysis technology for hydrogen production, viz.:

- Alkaline electrolysis technology.
- Solid oxide electrolysis technology.
- PEM electrolysis technology.

Alkaline is the nearer term technology for larger systems, whereas solid oxide electrolysis is in early development. The PEM technology seems to be more apt for small-scale applications (Kaufmann, 2003). Solid oxide electrolysis is a high-temperature electrolysis process. High-temperature steam electrolysis makes use of a high-temperature heat source (Herring, 2003).

Table 5-2 gives an overview of the current state-of-the-art and the expectations of electrolyser technology.

Table 5-2: Characteristics of electrolyser technology

Company	Type of electrolyser	Energy consumption [kWh/Nm^3]	H_2 production [$Nm^3/hour$]	Input Power Rating [kW]	Pressure [bar]	Efficiency [% LHV]
Norsk Hydro	Alkaline	4.1-4.3	Up to 485	50-300	0.5-1	61-72
	PEM?	4.8	Up to 60		~15	70-73
Teledyne		5.3-6.1	Up to 42	-	4-8	67-72
Energy Systems		5.6-6.4	Up to 150		8-15	66-71
Stuart Energy	Alkaline	5.9	>50	-	1-25	68-72
	PEM?	4-4.2	10-60	60-360	~25	73-75

The specific investment cost of electrolysers is expected to come down from the current level of \$1000-2500/kW for state-of-the-art alkaline electrolysers to – in the long term – \$300-500/kW for advanced electrolyser technology (Liu, 2003). According to (Wurster, 1994) the specific investment cost of electrolysers could come down to €700/kW in 2050 (ECU 550/kWe in 1994).

With regard to the experience with electrolysers until this date, Annex A gives an overview of worldwide hydrogen fuelling stations (Internet Source 7; The Clean Fuels and Electric Vehicles Report, 2003b). This overview hydrogen fuelling stations in the world gives the following result with regard to the sourcing of H_2 (Table 5-3).

Table 5-3: Sourcing of H_2 for hydrogen fuelling stations based on data from Table 2-2

	Delivered LH_2	Delivered compressed H_2	Central electrolysis	On-site electrolysis	H_2 from crude oil, natural gas, or methanol	Total
No of stations	18	5	1	19	8	51

Therefore, it may be concluded that delivered LH_2 and on-site electrolysis are the most widely applied ways to fuel hydrogen fuelling stations at this stage.

5.1.3. R&D development

Like for the automotive applications, the number of patents is used as proxy fro the R&D expenditures.

Table 5-4 gives the overview of public and business R&D over the last decade. The 1990 value is estimated based on the number pre-1990 patents compare to the post-1990 number of patents. Private or business R&D is supposed to be 63% of the total R&D, a fraction based on a global average for a number of technologies, not specifically for electrolysers.

Table 5-4: Cumulative R&D expenditure for electrolysers

million €2000	cumulative pubilc R&D	cumulative private R&D
1990	44	102
1991	46	104
1992	55	120
1993	67	139
1994	81	162
1995	97	189
1996	116	221
1997	128	241
1998	140	260
1999	147	272
2000	156	285
2001	158	289
2002	172	312

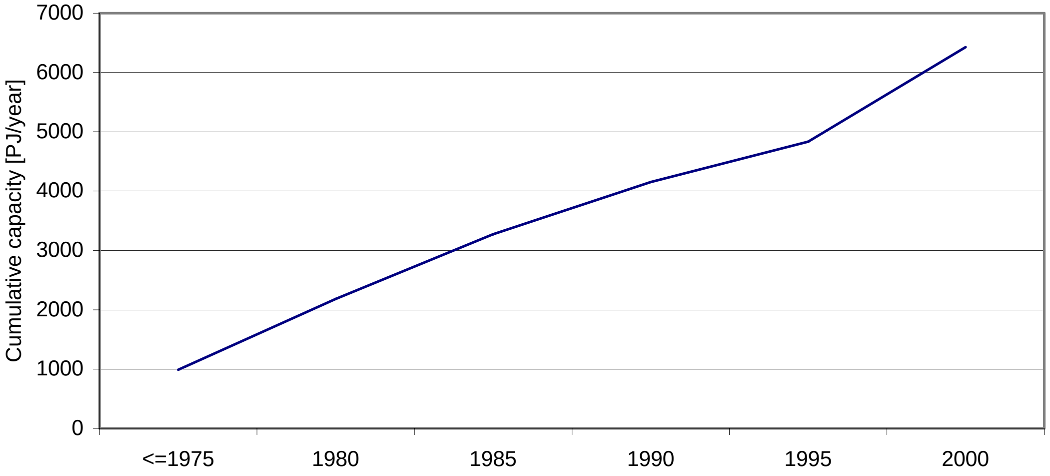
5.2. Liquefaction of LNG

Liquefaction is the process where through cooling a gaseous matter is converted to a liquid. At present, the technique is primarily used in transportation of natural gas. On a smaller scale, liquefaction is also used in handling of hydrogen. It may be expected that particularly the latter application may become the major process in the future, but spillovers between the two types of liquefaction is likely.

5.2.1. Cumulative capacity

The use of liquefaction for natural gas has had an extensive history. The first commercial liquefaction plant became operational in 1941 in the USA. International trade commenced from 1964 onwards, as the United Kingdom started to import LNG from Algeria. Since then, the number of large-scale facilities for liquefaction has gradually increased, as is shown in the figure below.

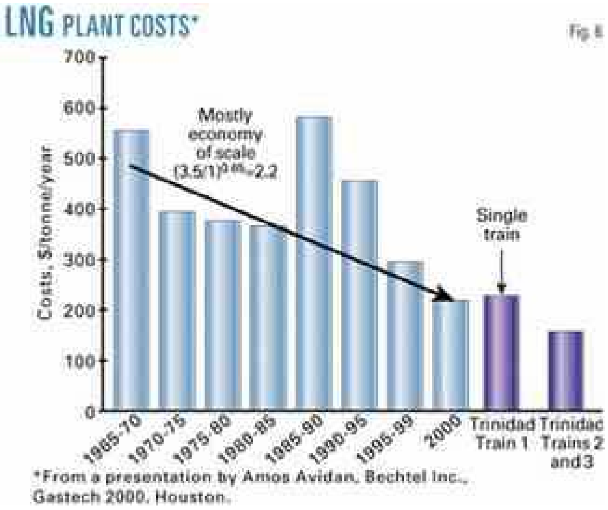
Figure 5-1: Cumulative capacity of Liquefaction plants for LNG



5.2.2. Specific costs of LNG

Specific costs for liquefaction have shown a gradual decline. However, this decline is partially due to expansion of existing production facilities, rather than the construction of greenfield plants (Shepherd, 1999). Moreover, as various concepts for liquefaction are implemented, large variances in specific costs may be found. On the one hand, this should be kept in mind when examining the relation between cost data and capacities. On the other hand, one might argue that such effects are part of the technological development, and should be reflected in an overall learning of liquefaction. The sparsely available data is given below.

Figure 5-2: LNG plant cost development according to Bechtel Inc.


LNG PLANT COSTS*

*From a presentation by Amos Avidan, Bechtel Inc., Gastech 2000, Houston.

Aside from the possible spill over with hydrogen on the long term, the importance of LNG on the shorter term will be to globalise the gas market. Where gas markets are generally local at present, as a result of pipeline limitation, continued growth of liquefaction capacity will clearly facilitate international trade in gas.

5.2.3. Research and development on LNG

There exist various types of liquefaction plants. In recent years these competing technologies have led to lower prices, but from the perspective of data gathering, this competition has one major drawback: data on business R&D expenditure is of strategic value, and hence hard to come by. Furthermore, on the side of governments the focus is on safety aspects, as becomes clear from the classification in the IEA R&D-database (IEA, 2004).

Because of the scarcity of data, combined with the focus on non-power technologies, it was decided not to include LNG-technologies in the project.

6. Heat Pumps

6.1. Introduction

Heating and/or air conditioning of buildings have been the preferred areas of application for heat pumps. Besides those there is also a number of commercial applications for heat pumps, e.g. heat supply for food processing or for the chemical industry. A very interesting field for the deployment of heat pumps can be drying processes, such as in the paper or textile industries, and the dehydration of sludges. Heat recovered by heat pumps can be used for drying goods; the cooling that is produced simultaneously is capable of separating steam fractions from air or gas flows.

For industrial purposes heat pumps with a thermal range from 200 kWth up to 2 MWth are available; for domestic heating, plants start from as little as single digit kW capacities.

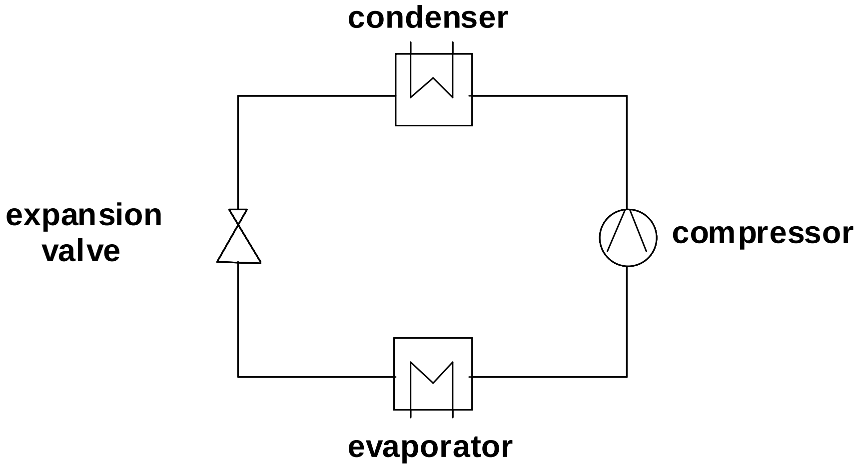
There are two operational modes for heat pump plants: monovalent mode, if the heat pump is the only heat supply in the circulation system, and bivalent mode, if another source of heat is integrated (e.g. an oil-fired boiler). Bivalent mode can optionally be performed with an alternative (“substitute”), parallel (“add-on”) or mixed operation of both sources.

Both heat pumps and refrigerating machines are based on the same thermodynamic principle. Heat is absorbed at low levels of pressure and temperature, and mechanical work is added to the system, so that the heat can be delivered at higher levels of pressure and temperature. Thus heat from the environment (ground, air or water) can be utilised, making the primary energy demand decrease (30 to 60%), which can save both costs and CO_2 emissions.

The particular application of the thermodynamic principle determines which term is used to describe the system. If the hot side of the system is utilised, it is called a heat pump; with the cold side utilised, it is called a refrigeration machine. The most common application of a refrigeration machine, of course, is the refrigerator that one can find in almost every household in Europe.

Heat pumps can reach a thermal maximum of 150 °C on their heat-output side. They are especially suitable for the climatisation of buildings. Besides providing heat the heat pump then produces cold by cooling water flows that can be used for cooling purposes. Generally, heat pumps consist of four essential components connected to each other by pipes (see Figure 6-1): Vapouriser, compressor, condenser and expansion valve. A liquid working fluid (refrigerant) with a very low boiling point runs through this system. Common refrigerants are, since the prohibition of the CFCs, ammonia, fluorocarbons, carbon dioxide and various types of hydrocarbons, e.g. propane, propene or pentane.

Figure 6-1: Major components of a heat pump



In the vapouriser the refrigerant absorbs heat from the environment to evaporate. The vapour runs into the compressor, where both pressure and temperature are raised by adding mechanical energy. In the condenser the vapour is condensed completely, releasing all the heat absorbed so far for further utilisation, e.g. for heating purposes.

Besides the sources and sinks of heat, the method of refrigerant compression is also variable. Smaller plants usually have electric or, from 100 kWth on, gas engine compressors. These plants are called compression heat pumps. Larger plants on industrial scales are able to apply waste heat flows for a thermal compression of the refrigerant. These plants are called absorption heat pumps. Thereby refrigerant vapour is blended with water, condensed and further heated by the waste heat flow (maximum temperature 180 °C), with pressure continually rising. The lower boiling point of the refrigerant enables the water fraction to separate from the blend. By cooling down water and refrigerant flows, the entire heat absorbed can be utilised. By analogy there are absorption and compression refrigerating machines.

The quality of a heat pump plant can be expressed by several ratios. The coefficient of performance (COP or ε) is defined as the ratio of the overall output of useful heat and input power of an electric powered compressor. The COP is an indicator for the efficiency of a heat pump process.

Similarly the primary energy ratio (PER or ζ) is the quotient of the overall output of useful heat and input power of the fuel. The PER gives information about current fuel efficiency in combustion engine and absorption heat pumps. Gas engine heat pumps can reach primary energy ratios between 1.5 and 3, whereas electric heat pumps for domestic heating have values between 3 and 4, due to the generally lower temperature level of their heat demand (Blesl, 2002; Leven et al., 2001).

According to both ratios, it is necessary for the heat source to have a rather high temperature level, and for the return to have the lowest temperature level possible, in order to reach maximum efficiency.

The seasonal performance factor (SPF or β), which is the quotient of overall output of useful heat and overall input energy, is the basis of the long-term economics of the plant, generally calculated as the annual performance factor. Heat pumps connected to plate heat exchangers have annual performance factors of some 3.8; if connected to floor heating systems the number is about 4.3, due to their temperature level being 20 K lower. Large plants with small temperature differences can peak at annual performance factors of some 7.2 (Bertuleit, 2000).

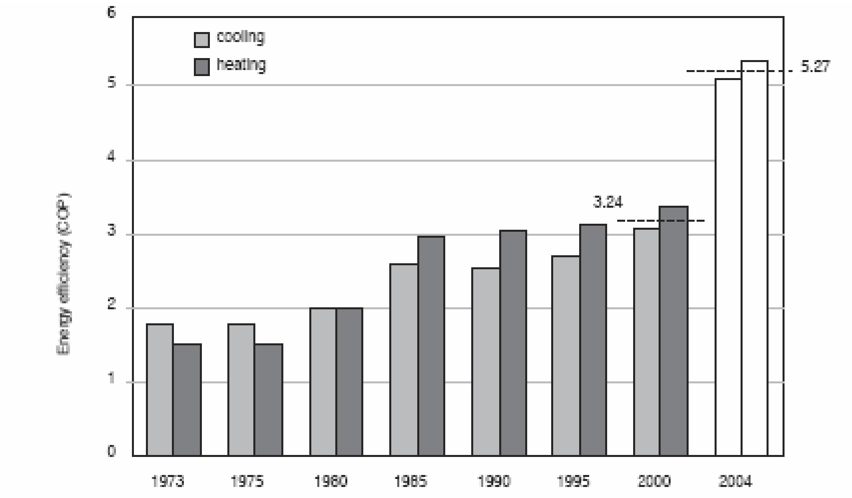
Because the heat taken from the environment is only contained in the numerator, yet not in the denominator, it is possible for all three ratios to have values higher than 100 %.

A new opportunity for a rational use of energy arises from the combination of a compression heat pump and combined heat and power unit (CHP). Hence the constant power-heat-ratio of the CHP can be varied and an independent energy supply system providing electricity, heat and cooling can be realised.

Current research topics in the heat pump area concern the use of natural refrigerants, smart control systems, and cost reduction. Also on the agenda are items like extended maintenance rates, advanced flue gas cleaning and optimised components.

The idea of using environmental heat is not quite new: The concept of using the ground as the heat sink for a geothermal or ground-source heat pump dates back to the 1940's. (Sanner, 2001) The first ground-source heat pump in the U.S. was installed in a house in Indianapolis in 1945. (Rawlings, 1999). During the last 30 years heat pumps have made considerable progress, also in terms of energy efficiency. So COPs of small residential heat pumps soared from 1,5 in 1973 to 3,24 in 2000. For 2004 COPs larger than 5 were predicted. The development of heat pump energy efficiency is shown in Figure 6-2.

Figure 6-2: Trend of energy efficiency for residential heat pumps up to 2,5 kWth *(IEA Heat Pump Centre Newsletter, vol. 21, 1/2003)*



6.2. Market survey for selected countries

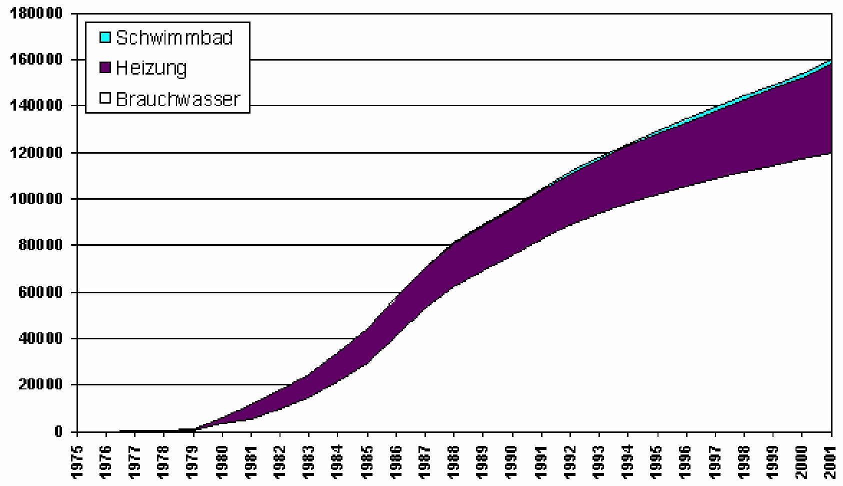
The following chapter describes the development of international heat pump markets during the last 25 years. Emphasis is put on countries in Western Europe plus Japan. Besides, there will be a glance at the North American and the upcoming Chinese market. For markets with sufficient data available, learning curves were constructed.

6.2.1. Austria

In Austria, the first heat pump systems installed in the early 1980's were either monovalent systems with groundwater as heat source and a low-temperature heat distribution system (floor heating) or bivalent systems with outside air as heat source and a high-temperature heat distribution system using radiators. Monovalent systems were installed in new buildings; bivalent systems were mainly used for retrofitting existing heating systems (Halozan, 2003).

In the early 1980's, oil was the main fuel for space heating in the residential area. The price ratio of electricity to heating oil per unit of energy delivered was roughly 2.5. In order to stimulate the introduction of heat pumps, the government provided subsidies in the form of tax deductions. The result was not only a rapid rise and peak in the number of units sold and installed, but also in the number of heat pump system failures. The integration of the heat pump in the heat distribution system of the building proved to be the cause of most failures.

Figure 6-3: Cumulative sales of heat pump units in Austria 1975-2001

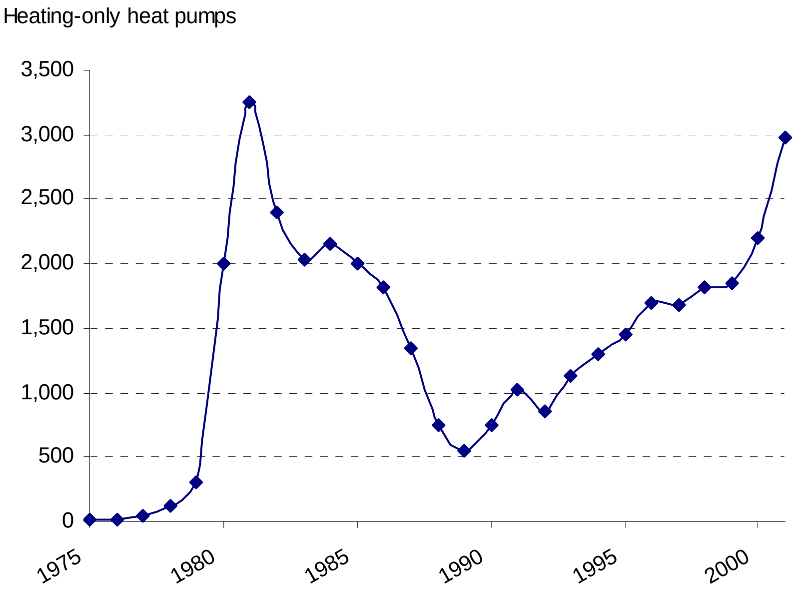


By the end of 2001, nearly 160,000 heat pumps (for space heating, warm water supply, swimming pools) were in operation in Austria, about 77% of which for hot water, and the balance for space heating. In 2001, the capacity of heat pumps (space heating, hot water, etc.) amounted to 834 MWth, and the annual heat production was nearly 2,000 GWhth (Internet source 9).

Figure 6-4 shows the development of heating-only heat pumps. (Halozan, 2003; Bach, 2003) After a steep reduction in numbers of heat pumps installed in 1982, energy companies focused on solving the problem of servicing customers with heat pump systems. In 1985, international oil prices tumbled and government subsidies for heat pump systems were cancelled. Bivalent systems, which until that date had formed the main market, were not cost-effective any more. The heat pump market focused on monovalent systems for new buildings. Later on, the ground was also introduced as a heat source. Ground coils were mainly horizontally installed collectors.

Since 1990, the heat pump market showed a steady recovery. The ground (or groundwater) became the main heat source and, due to better building codes (i.e. better insulated houses, improved compressors and heat exchangers), SPFs in the range of 4 and more have been achieved, especially with direct expansion systems.

Figure 6-4: Annual sales of heating-only heat pumps in Austria 1975-2001



Heat pump capacities installed in Austria from 2000 to 2003 are shown in Table 6-1

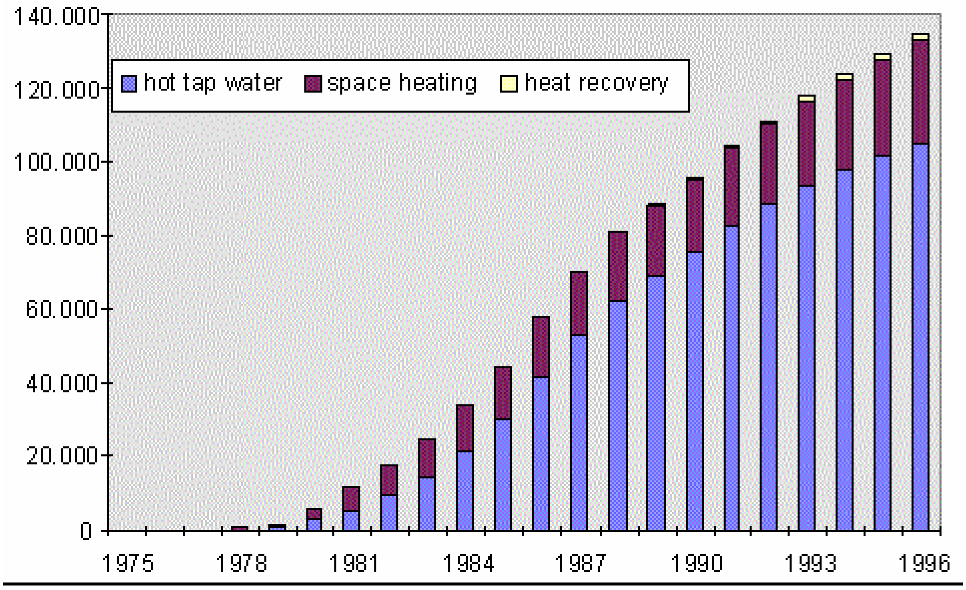
Table 6-1: Heat pump installations in Austria 2000-2003 according to field of application (Faninger, 2004)

year	water for	heating	air conditioning	swimming pool	total
	domestic/industrial use				
2000	2700	2000	80	90	4890
2001	2400	2200	120	120	4840
2002	2300	2800	160	100	5360
2003	2200	3500	180	100	5980

From 2002 on, the figures for water for domestic/industrial use and for heating applications were extrapolated, the data for air conditioning and swimming pools are based on estimations.

Figure 6-5 shows the environmental benefits of heat pump application for Austria in terms of CO_2 reduction by heat pumps (space heating, hot water, etc.) in Austria. In 1996, for example, the production of some 130,000 t of CO_2 could be avoided by heat pump operation.

Figure 6-5: Cumulative CO_2 reduction by heat pumps in Austria [tonnes CO_2]



6.2.2. Canada

The former Canadian Earth Energy Association reported that about 30,000 ground-source heat pump units had been installed in Canada in the nineties. Annual sales peaked in the early 1990s, primarily as a result of a utility incentive program in the province of Ontario, enabling installation of approximately 6,700 residential ground-source heat pumps. (Internet source 10) The Geothermal Heat Pump Consortium (GHPC)[2] is a partner and counterpart to the Canadian GeoExchange Coalition. In March 2000, Natural Resources Canada (NRCan) proposed to pay $0.87 million over three years to the GHPC. (Internet sources 11 and 12)

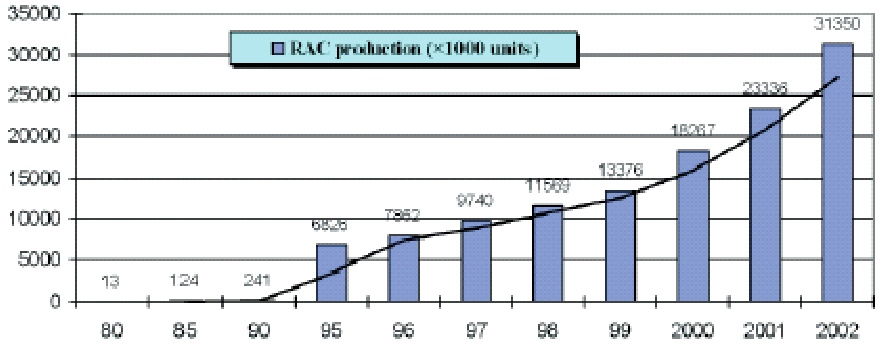
---

[2] The Washington based GHPC is a non-profit organisation (partnership) of government, industry and over 240 utilities.

6.2.3. China

The Chinese heating market is, to a large extent, characterised by the absence of central heating systems. Instead, room air conditioners (RAC) are usual. Due to its large population, China has the biggest residential air conditioning market in the world.

Figure 6-6: Room air conditioner production in China (IEA HPC Newsletter vol. 22, 4/2004)

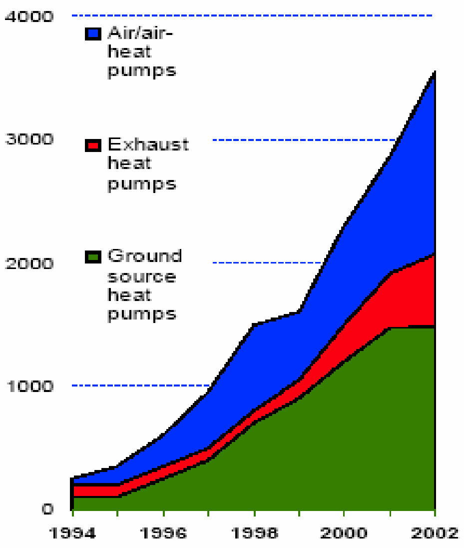


Therefore, the production of RACs in China ranks first in the world. For example, penetration of residential air conditioning in Shanghai has reached 96.8%. However, the usage ratio is still low due to high energy costs. Use of large numbers of RACs has already caused enormous pressure on energy supply and the environment of China. Electrically driven RACs have created the biggest unstable power grid load and the biggest source of CO_2 emissions in most Chinese metropolises. The residential air-conditioning trend in Chinese metropolises should be DHC with CCHP using natural gas as an energy source. Household central air conditioning will become the main type of air conditioning for individual houses or town houses. RACs will still have a broad market (IEA HPC Newsletter vol. 22, 4/2004).

6.2.4. Finland

The cumulated sales of heat pumps in Finland 1994-2002 is shown in Figure 6-7. A steady growth of the Finnish heat pump market can be confirmed. This increase of sales does yet not apply to all kinds of heat pumps offered: Whereas the outlets of ground source and exhaust heat pumps have almost been stagnating since 2000, air/air heat pumps have shown dynamic growth, especially after 1999.

Figure 6-7: Heat pump sales in Finland for different heat sources (Hirvonen 2003)



There are a couple of reasons for the general growth of the heat pump sector, like rising energy prices, the tough Finnish climate conditions, etc. Besides, electricity is the only energy carrier with a nationwide distribution system. As Finnish homes have high air change rates, air/air systems recovering heat from waste air are very attractive. Thus, this kind of heat pump has outperformed the other heat pump technologies in terms of sales and market growth during the last few years.

The factors mentioned above make Finland a very attractive market for heat pumps in the future, and so further growth is expected for the next years. Furtherly, Finland has a great many of lake and rock areas, where solar heat is stored. The ongoing trend towards heat pumps will additionally be fanned by the chance to utilize these sources.

6.2.5. France

Table 6-2 compares the investment and operating costs of various types of heat pump systems with a heating/cooling floor under French conditions. (Olivier, 2001)

Table 6-2: Comparison of the costs of heat pumps for a heating/cooling floor application

Type	investment cost	operation and maintenance cost
	[€/m^2 floor area]	[€/m^2 floor area/year]
vertical ground-coupled system	137	2.6
horizontal ground-coupled system	115	2.6
air-to-water heat pump	92	3.8

The seasonal COP during the heating period varies from 3.6 to 3.9 for heat pumps in France. Table 6-3 shows investment cost of ground-source and air-to-water heat pumps and that of an oil-fired heating system. (Internet source 13; EHPA, 2003)

Table 6-3: Investment cost of heat pump systems compared with oil-fired central heating

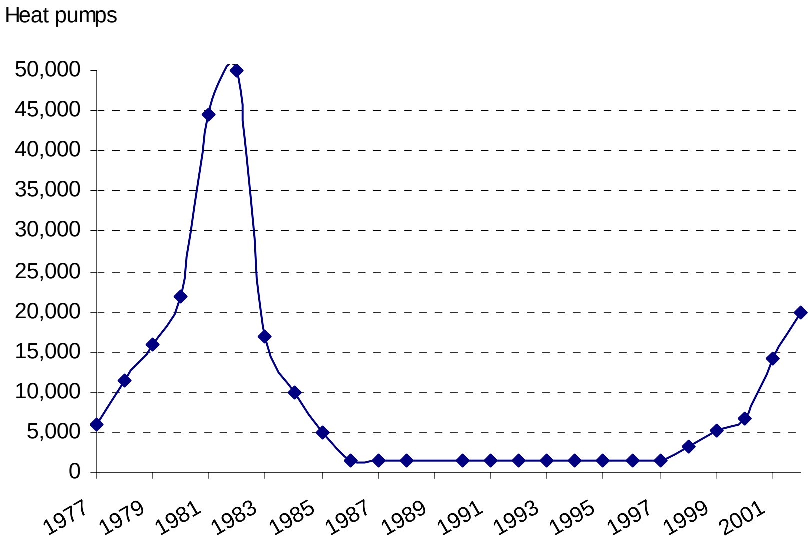
	heat pump system based on floor heating[1]		oil-fired
	air-to-water heat pump	ground-source heat pump	central heating
	[€]	[€]	[€]
drilling on turn-key basis	-	7,000	-
heat pumps	N/A	6,000	-
installation of heat pump	N/A	1,200	-
oil-fired boiler	-	-	4,800
Control	-	-	800
fuel tank + installation	N/A	2,500	3,800
Chimney	-	0	4,000
Total	10,000	16,700	13,400

[1] Based on a heat demand of 7 kW$_{th}$ and an average COP of 3.

According to Table 6-3 the additional investment cost in case of a ground-source heat pump is €3,300, and the cost saving in case of an air-to-water heat pump is €3,400.

Figure 6-8 shows the annual sales of heat pumps in France according to (EHPA, 2003). In 2002, sales of heat pumps soared to 20,000.

Figure 6-8: Annual sales of heat pumps in France 1977-2002

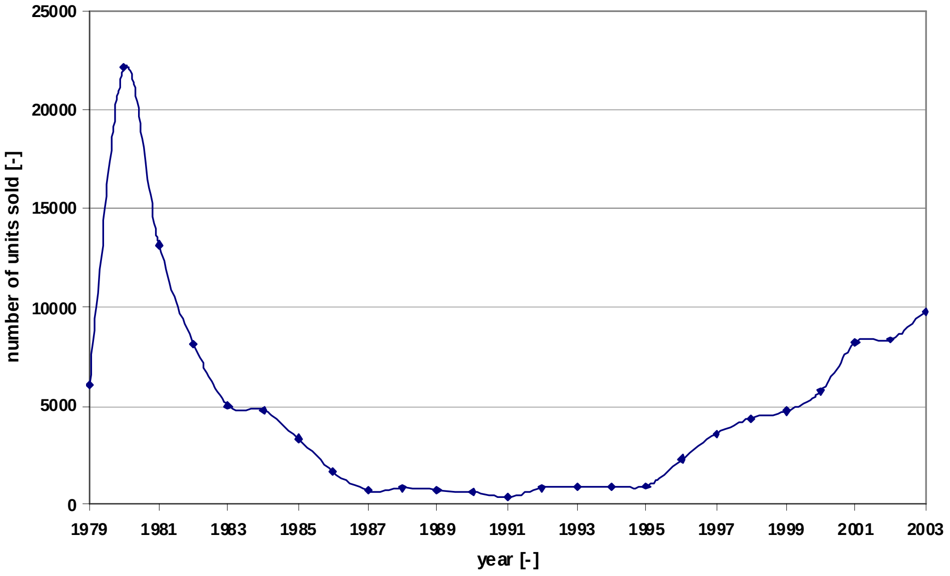


In 1996/1997 ADEME and the Ministry of Housing supported development and field tests by manufacturers of prototypes of engine driven heat pumps for individual housing with a budget of 300 k€. Details about the financial incentives for heat pumps for the residential sector are presented in (EHPA, 2003). EdF has decided to develop both heating and cooling solutions. However, no data with regard to private R&D (e.g. by EdF) have been disclosed.

6.2.6. Germany

Information of the heat pump sales figures, as shown in Figure 6-9, points out substantial differences especially in the early eighties. Since the foundation of a governmentally supported heat pump centre in 1991, information on sales figures is collected centrally and used for general statistics. The heat pump peak in Germany was at the beginning of the eighties, but after some years, the sales figures collapsed downright. In the late eighties and the early nineties, they ranged at a few hundred heat pumps. Since the middle of the nineties, an upward trend appeared, although the sales figures still lag behind the numbers of the early eighties. (Nilsson, 2003; Internet sources 14 and 15)

Figure 6-9: Annual sales of heating-only heat pumps in Germany 1979-2003



In 2003, not only 9,745 heat pumps for heating were sold (as shown in Figure 6-9), but another 3,776 systems for warm water supply were installed. This totals to 13,521 sales, reaching closely to the all time high of 1980. The largest growth in 2003 was performed by air/water heat pumps (+57 %), followed by heat pumps using ground heat (+16 %), whereas heat pumps using heat from water showed a 20 % decline (Wärmepumpe aktuell vol. 6, 1/2004).

Federal R&D support for heat pumps declined after a peak since the early 1980's, just like R&D support in general. Funds were used to promote R&D by research institutes, manufacturers of heat pumps, etc. Federal R&D support from 1974 to 1998 amounted to DM 15 mln (≈ € 7.5 mln).

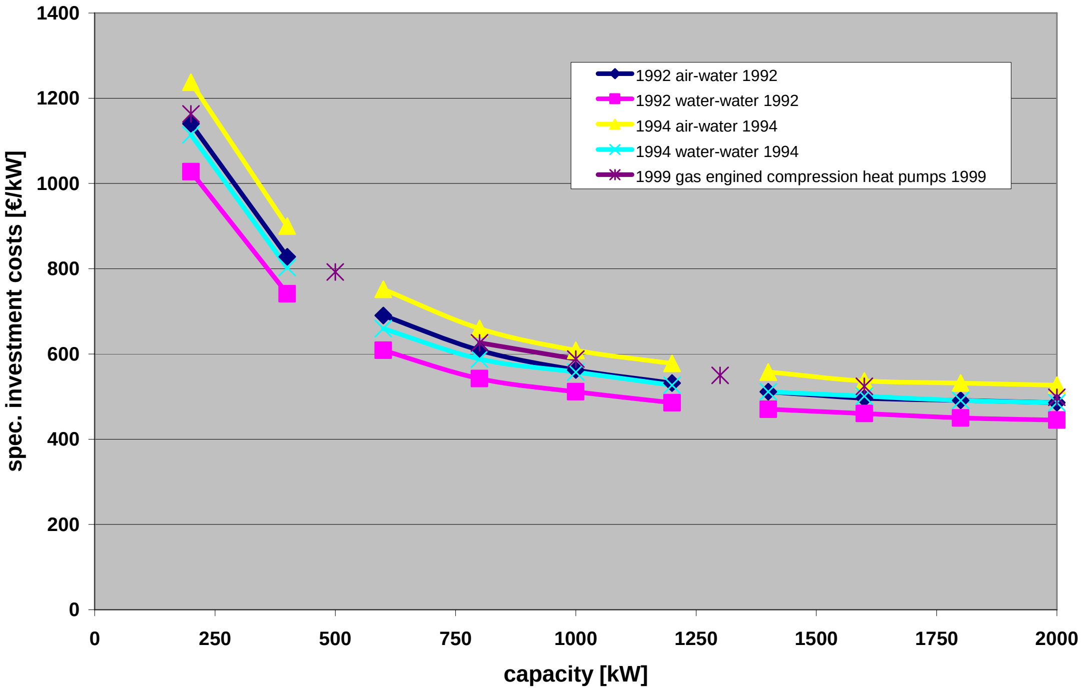
Although the Federal government no longer supports heat pumps by grants, there are attractive loans for heat pumps. Grants are awarded in the framework of the CO_2 reduction programme and the buildings retrofit CO_2 programme of the KfW (Kreditanstalt für Wiederaufbau). (Internet source 16)

In 1997, the investment cost of an electric heat pump system based on 5 vertical borehole heat exchangers (double-U), each 50 m deep, amounted to €23,300 (DM 45,600). The heat pump supplies the heat demand and the demand for hot water. Some cooling may be provided using the floor heating coils. The floor area is 180 m2 in two storeys, with a nominal heat demand of 11.5 kWth. Thus, the specific investment cost was about €2,000/kWth in 1997, including drilling costs. (Internet source 14)

The investment costs of heat pumps have increased slightly during the past few years. For industrial applications (see Figure 6-10) they were in a range between 1250 €/kW and 450 €/kW (EWU 1992, 1994, 1999).

For residential application, typical annual operation costs consist of a 77.6 % share for capital costs (2023 €), 2.9 % fixed costs (508 €) and 19.5 % variable costs (77 €) (example for a single occupancy house equipped with steel panel radiators erected in 1995) (Leven et al., 2001).

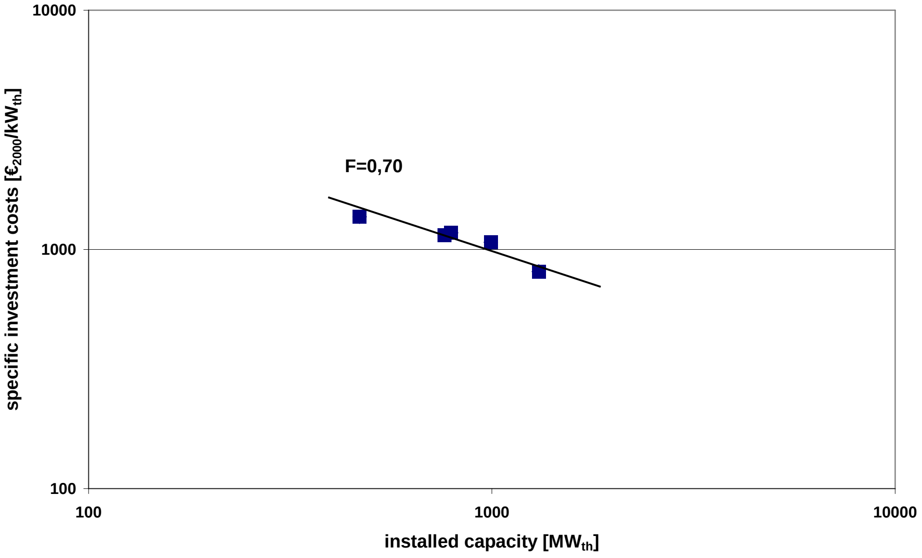
Figure 6-10: Investment costs for different types of heat pumps for industrial use in different years (EWU 1992, 1994, 1999)



From the data for cumulated sales and the investment costs associated, a learning curve for Germany´s heat pump market can be derived. This learning curve is shown in Figure 6-11.

With increasing cumulative sales, a inflation-adjusted contemplation of investment costs shows a steady decline. So, the learning factor arising for the years 1980-2002 is 0,70. Later on, there will be another learning curve for the Swiss heat pump market, that can be compared to the result for Germany.

Figure 6-11: Inflation-adjusted learning curve of the German heat pump market 1980-2002 (cost data from EWU and BWP)



6.2.7. Japan

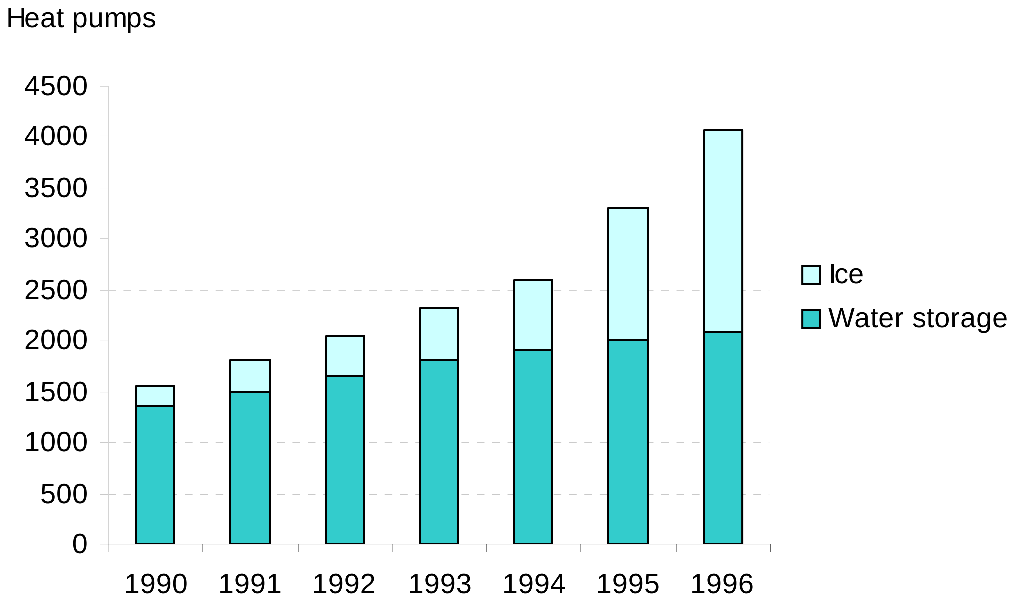
The Heat Pump & Thermal Storage Technology Center of Japan (HPTDJ) is a public organisation functioning under the auspices of the Ministry of Economy, Trade and Industry (METI). As a national centre for heat pumps and thermal storage, the HPTCJ promotes the use of thermal storage systems and carries out many projects aimed at improving technology. Thermal storage systems combine the advantages of heat pumps and thermal storage, so they meet the need for the effective storage and utilization of energy. CO_2 heat pump water heaters sold in Japan are of the storage type that store the hot water produced with cheap night-rate electricity in a tank.

The HPTCJ is actively involved in promoting systems and technologies in this field, and we conduct a wide range of surveys and research. Government subsidies are available to support the installation of ice thermal storage air conditioning systems. Subsidies apply to decentralised systems. (Internet source 17)

A relatively small use of heat pumps is indicated which is concentrated in the cold and snowy Prefecture of Okayama. Hot spring water above 150 °C is available all over the country so there is little demand for heat pumps. (Lund, 2000a)

Figure 6-12 shows the cumulative number of heat pumps in Japan (Halozan, 1998).

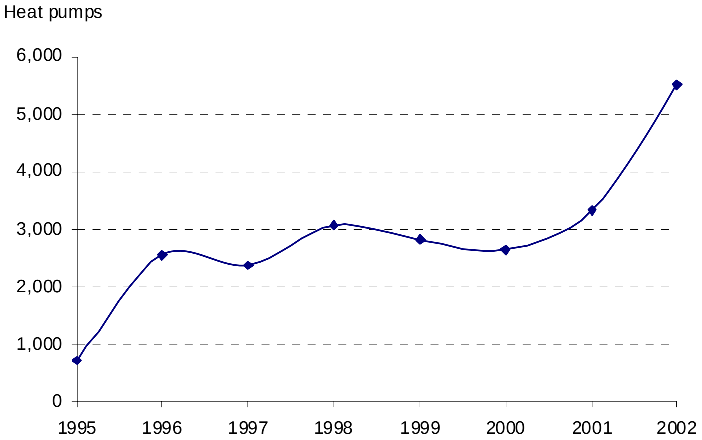
__Figure 6-12: Cumulative number of thermal storage type heat pump systems in Japan 1990-1996__



6.2.8. The Netherlands

According to (NeoScan Warmtepompen, 2003) and (Joosen, 2003) at the end of 2002 the heat pump capacity in the Netherlands amounted to 274 MWth. The number of heat pumps was approximately 33,200, including about 8,400 heat pump boilers. (Graus, 2003) (Figure 6-13)

__Figure 6-13: Annual sales of heat pumps in the Netherlands 1995-2002__

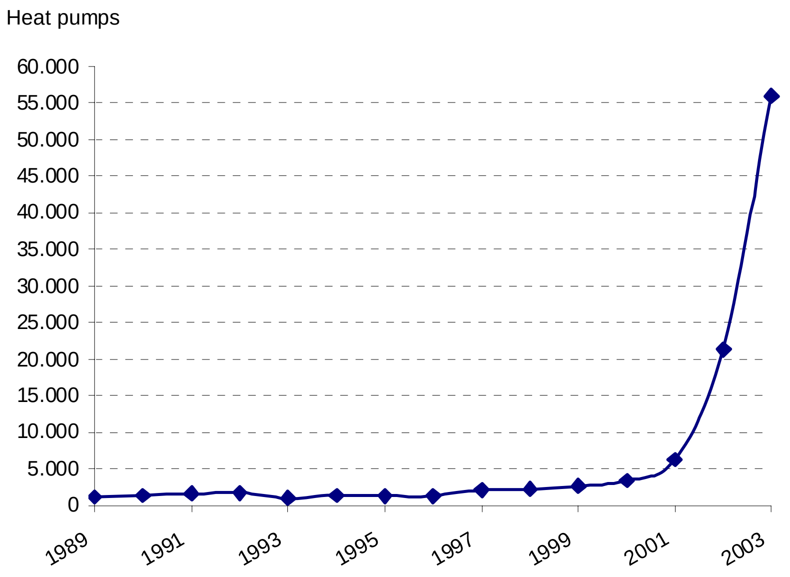


R&D and the quality of prototypes and commercial heat pump technology in the Netherlands has improved dramatically in the last few years. Seven years ago (in 1998), the international position of the Netherlands is this regard was really poor. In the meantime, however, heat pumps have been introduced successfully in the horticulture sector and several very interesting heat pump applications in the residential (domestic) sector have been observed recently. This has been realised by a coherent approach both from the government and NOVEM, the Dutch organisation for promotion of R&D on energy and environment, and several Dutch manufacturers (Kleefkens, 2004).

6.2.9. Norway

In 2003, sales of heat pumps in Norway reached 56,000 units (after 21,300 in 2002 and 6,400 in 2001, 94% of which in the residential sector). Since 1997, market sales show a rising trend. Higher electricity prices in the Nordic energy market were the main reason for increased sales of heat pumps in Norway in the last few years. A substantial part of the production in this market is hydropower and periods with cold and dry weather are resulting in higher prices. By the end of 2002, approximately 58,300 heat pumps were in operation in Norway. (Internet source 18) (Figure 6-14)

Figure 6-14: Annual sales of heat pumps in Norway 1989-2003



The Norwegian Heat Pump Association, NOVAP, (Internet source 19) assumes that the best way to promote market expansion is by:

- Quality assurance activities, i.e. certification of sellers/buyers, standard contracts and guarantees, and product information to potential buyers.
- Buyer support through insurance and loan arrangements.
- Information for potential buyers on the impact of heat pumps on energy consumption.
- Good statistical data on sales, etc.

6.2.10. Spain

The Spanish heat pump market has increased considerably in the past few years. Sales increased by 250% between 1997 and 2000 and about 2,000,000 heat pumps are installed at present. This growth rate is expected to continue for the next few years.

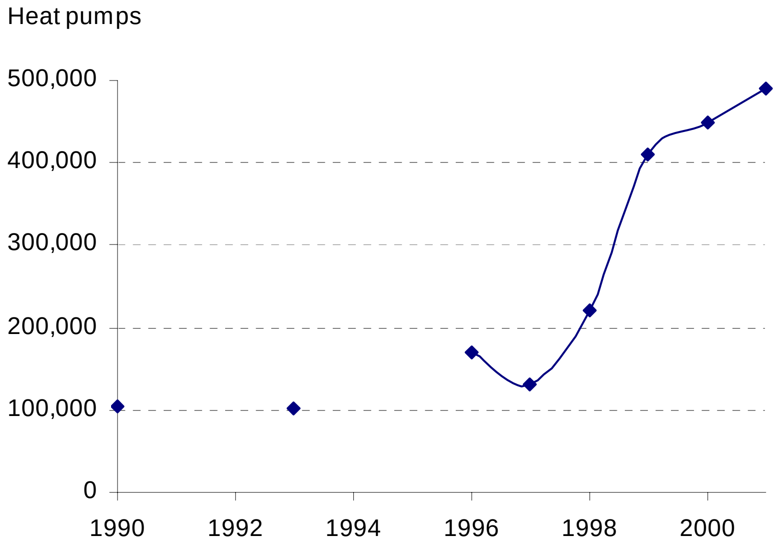
The air-to-air heat pump is the most successful type in Spain, especially in mild climate zones. The most common heat pump used is the electrically driven reversible compression unit, but gas companies are strenuously promoting gas-driven heat pumps. Heat Pumps have been installed in all sectors, but market penetration has been different in each one. The residential sector has the greatest number of installed heat pumps, followed by the commercial sector, with the industrial sector having the smallest number of sales. One of the most important barriers that must be overcome by the heat pump is the confusion in the minds of users. Most of them perceive the heat pump as air conditioning because equipment sold in Spain is normally reversible. In addition, the Spanish are not used to heating by air and prefer heating systems such as radiators. Heat pumps are normally installed as refrigerating equipment and a complementary heating system.

Nevertheless current promotional campaigns are focussing on public information and people are becoming increasingly interested in new heating systems, such as under-floor or ceiling heating. (Internet source 20)

The Spanish National Team on Heat Pumps (ENEBC) was created on 1st April 1996 at the request of the Ministry of Industry and Energy, through the State Energy Planning Office, for the research, development and dissemination of the heat pump technologies. (Internet Source 21)

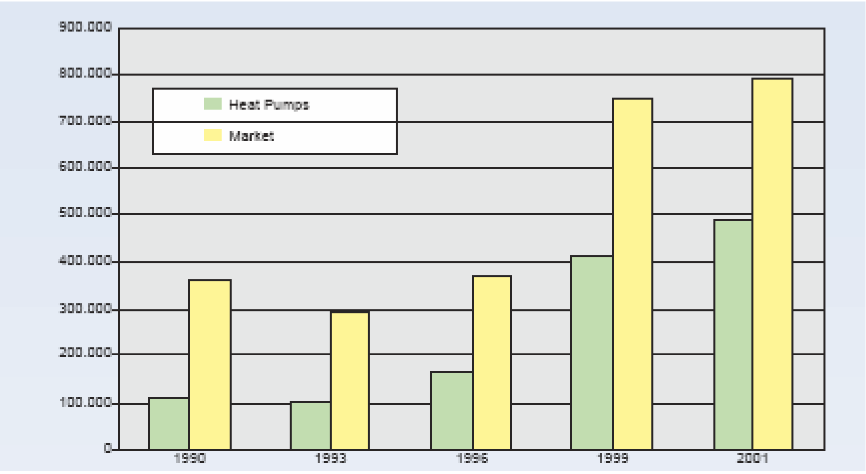
Figure 6-15 shows the annual sales of heat pumps in Spain (European Heat Pump News, 2002b; IEA Heat Pump Centre Newsletter, 2003)

Figure 6-15: Annual sales of heat pumps in Spain 1990-2001



As shown in Figure 6-16, heat pumps have the largest market shares for air conditioning applications. It also shows, that not only heat pump sales are rising, but there is also a steady growth in the entire market for air conditioning systems.

Figure 6-16: Heat pump and total air conditioner market of Spain (in units sold) (IEA Heat Pump Centre Newsletter, vol. 21, 2/2003)



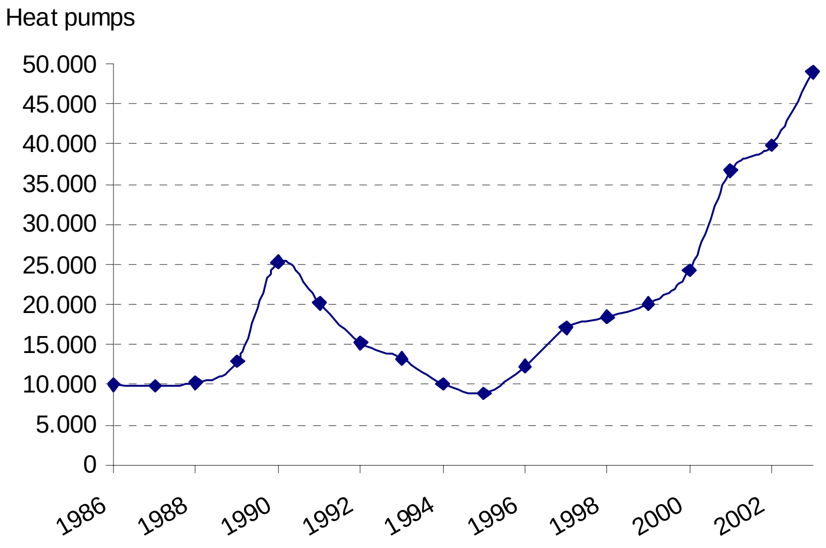
By the end of 2001, close to 2.5 million heat pumps were in operation in Spain.

6.2.11. Sweden

The Swedish heat pump market is one of the largest in the world. In 2002, total sales of heat pumps approached the level of 40,000. In the 1980's and 1990's Swedish market had its ups and downs illustrated by Figure 6-17 (Karlsson, 2003).

During the first half of the 1980's horizontal ground-source heat pumps and open systems were quite common in Sweden. During this period the heat pump market was supported by governmental subsidies. Around 1985, the heat pump market showed a substantial decrease, mainly due to the withdrawal of governmental subsidies. What is more, the international oil price decreased by some 50% at that time. During the period 1985-1990, the market consisted mainly of ordinary, non-expensive, heat pumps. Direct expansion systems were used for ground-source units. Air-to-water heat pumps were still quite common.

Figure 6-17: Annual sales of heat pumps in Sweden 1986-2003



Around 1990-1991, the heat pump market expanded again because of increased sale of air-to-air heat pumps. These were installed in houses with direct-acting electric heating. In 1994-1995, the Swedish National Board for Technical Development (NUTEK) issued a technology procurement on heat pumps. Consequently, sales of heat pumps increased rapidly.

6.2.12. Switzerland

Switzerland claims position number two in the European heat pump market, after Sweden. With 40% of new single-family homes equipped with a heat pump system, the market continues to grow. Fifty percent of the heat pump systems extract heat from the air, 39 % from the ground, using deep boreholes (300 meters), and 11 % from ground and surface water.

The Swiss try to ensure that in the next ten years more than 50 % of new dwellings and 10 % of the existing ones will use heat pumps. Training of installers and designers is a key element of the Swiss strategy (IEA Heat Pump Centre Newsletter, 2002). Table 6-4 gives an overview of the Coefficient of Performance (COP) that may be achieved with different heat pump configurations. (Heat Pump Test Centre Töss, 2003)

Table 6-4: COP's for different heat pump configurations measured in Töss (Switzerland)

Type	Temperature [°C]	Temperature heat source [°C]	Average COP
Air-water	35	-7 – 20	2.6 – 5.0
Brine-water	35	-5 – 5	3.7 – 5.0
Water-water	35	10-15	5.5 – 6.2

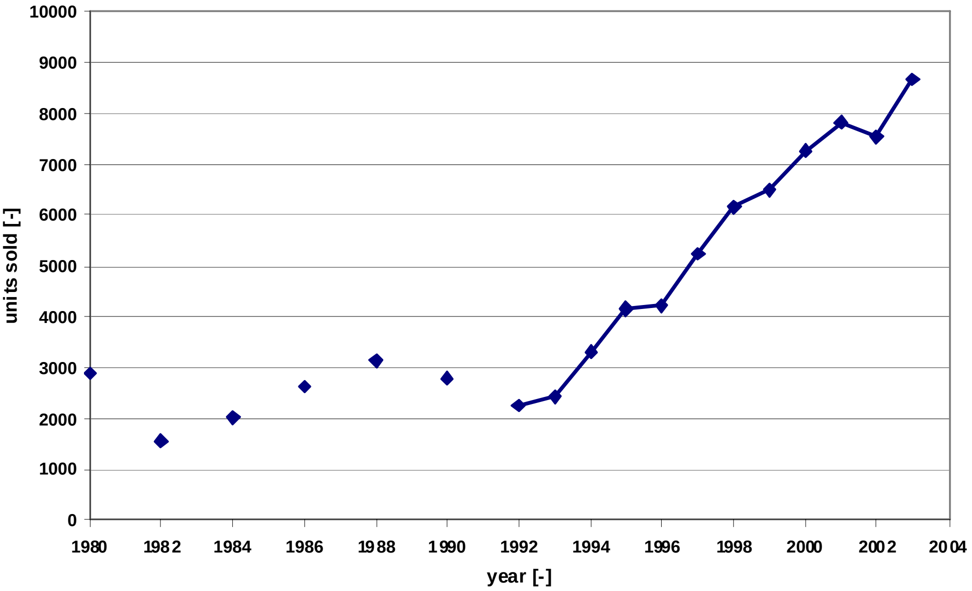
Table 6-5 compares the costs of an electric heat pump to those of an oil-fired central heating system. (Internet source 22)

Table 6-5: Comparison of installation and operational costs of an electric heat pump system with an oil-fired boiler (central heating system)

		Heat pump system with borehole heat exchanger	Oil-fired boiler (tank 2·2000 l)
Base: heat demand 6.5 kW			
Heat demand	[kWh/a]	13,600	13,600
System efficiency	[%]	95	80
Seasonal Performance Factor		3.5	-
Effective energy used	[kWh/a]	4,090	17,000
Fuel consumption	[l/a]	-	1,703
Space required	[m^3]	2.6	23
CO_2 emission	[tonne/a]	-	
Installation costs			
Complete system incl. storage	[€]	8,700	11,150
Borehole heat exchanger	[€]	7,530	-
Space in house	[€]	710	6,290
Miscellaneous (trenches, chimney)	[€]	1,110	1,090
Total installation cost	[€]	18,050	18,530
Energy costs			
Electricity, high tariff	[€/a]	230.75	33.50
Electricity, low tariff	[€/a]	153.85	15.00
Basic payment	[€/a]	69.75	5.50
Fuel cost	[€/a]	-	792.00
Total energy cost	[€/a]	454.35	846.00
Running costs			
Maintenance	[€/a]	102.60	253.00
Chimney cleaning, flue gas control	[€/a]	-	123.00
Total running cost	[€/a]	102.60	376.00

The investment costs of the ground-source heat pump in Table 6-5 is about 8% higher than the corresponding cost in Table 6-3. The investment cost of conventional central heating system is 40% higher, as Table 6-5 includes €6,290 for space required for the oil-fired boiler. The development of the Swiss heat pu4mp market is illustrated by Figure 6-18. During the last 12 years a steady upward trend in heat pump sales can be seen.

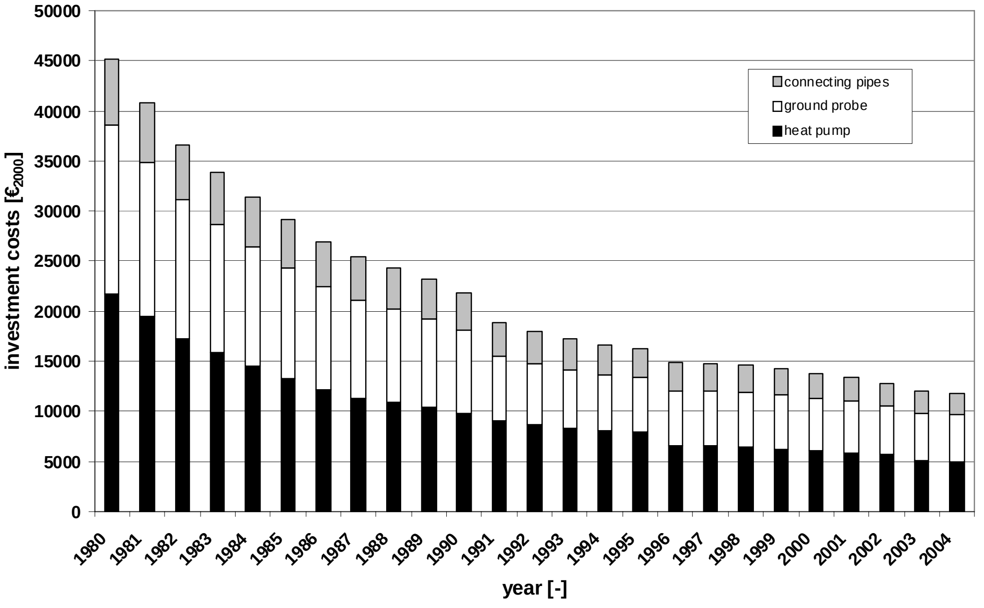
Figure 6-18: Annual sales of heat pumps in Switzerland 1980-2003 (Beyeler, 2004)



At the end of 2003, 86,000 heat pumps were in operation in Switzerland, with a total capacity of approximately 1,440 MWth. At the end of 2000, the number of heat pumps was 61,606, with an installed capacity of 1,038 MWth. (Rognon, 2002) Rybach et al (Internet source 22) expect that the market will further expand in the leading countries like Sweden and Switzerland.

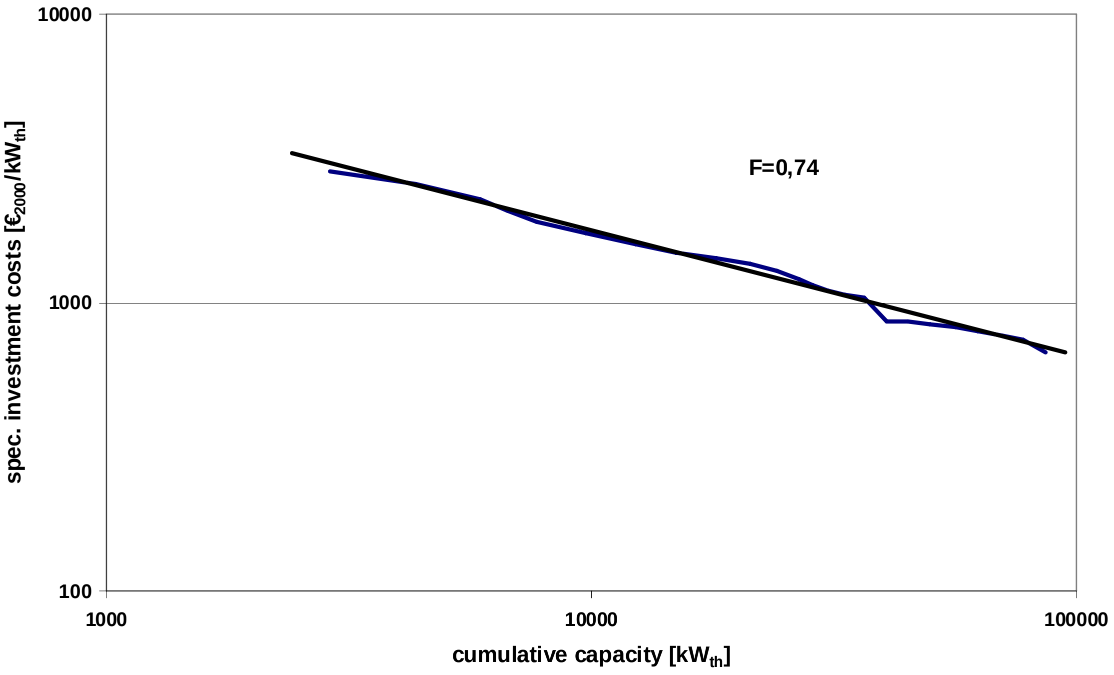
The inflation-adjusted development of the investment costs for a 7,6 kWth heat pump, boreholes and connecting pipes from 1980 to 2004 is shown in Figure 6-19.

Figure 6-19: Inflation-adjusted development of investment costs for a 7,6 kWth B0/W35 heat pump in Switzerland (base year 2000) (Beyeler, 2004)



Utilizing data from Figure 6-18 and Figure 6-19, a learning curve for the Swiss heat pump market can be calculated (see Figure 6-20). The resultant average learning factor for the Swiss market is 0,74.

Figure 6-20: Inflation-adjusted learning curve of the Swiss heat pump market 1980-2003



This comes close to the result for the learning factor of the German heat pump market, which is 0,70. Due to the larger scale of heat production in Germany the advantage from learning is even a little better there.

Figure 6-21 illustrates the development of geothermal heat production in Switzerland.

Figure 6-21: Geothermal heat production(before the heat pump) in Switzerland

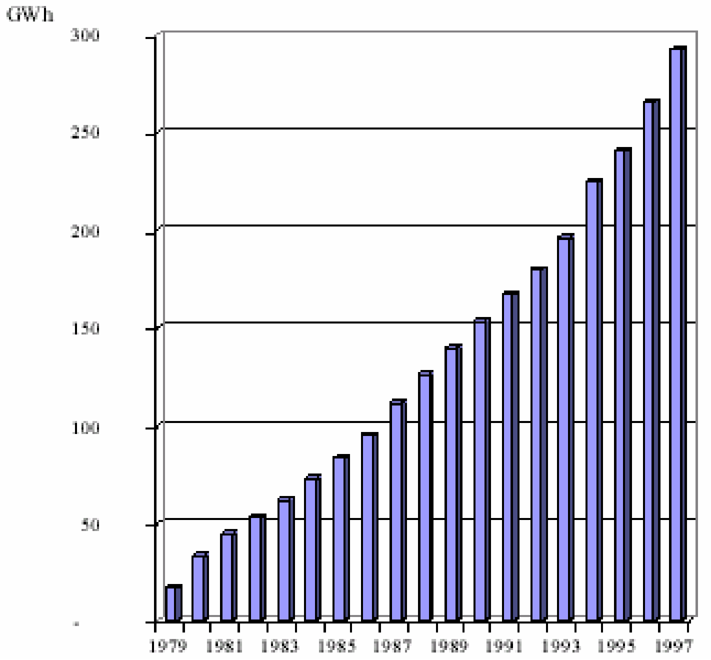
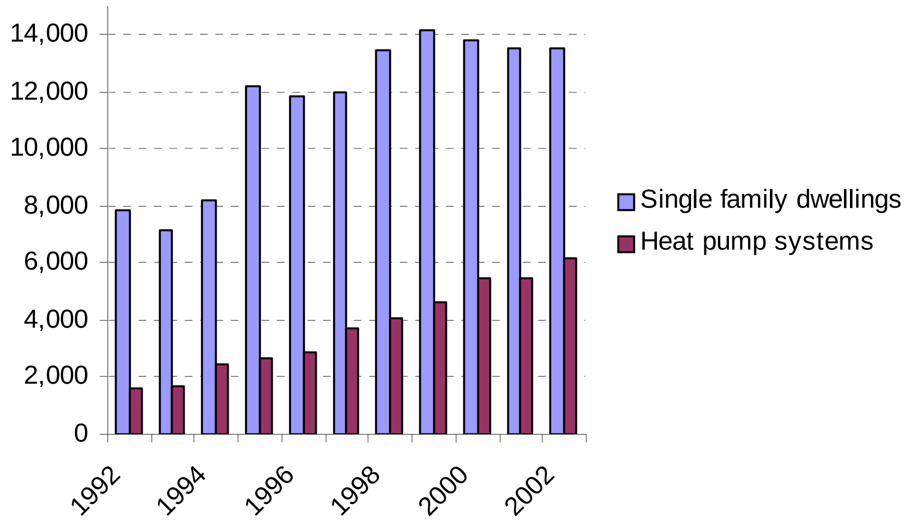


Figure 6-22 shows the increased share of heat pumps in new single-family dwellings in Switzerland. (Internet sources 23 and 24)

Figure 6-22: Penetration of heat pumps in new single-family dwellings in Switzerland



In 2001, the budget of the Swiss government for R&D on heat pumps (‘Umgebungswärme’) amounted to some CHF 1.5 mln (≈ €1 mln). (Internet Source 25)

6.2.13. United States

In the United States, geothermal heat pump installations have steadily increased over the past 10 years with an annual growth rate of about 12%, mostly in the mid-western and eastern states from North Dakota to Florida. Relatively few heat pumps have been installed in the west. At the end of 1999, a total number of 400,000 units installed, with 45,000 installed annually. Today these figures are 450,000 and 50,000, respectively. (Internet sources 26 and 27)

Historically, the fortunes of the electric heat pump have varied inversely with the fortunes of natural gas. Unitary heat pumps got a boost in North America in the mid 1970’s when the oil crisis and the moratorium on new natural gas hookups let to the proliferation of heat pumps in the newly developing suburban areas. However, poor installations and reliability problems kept heat pumps from becoming as popular as they might have been. Heat pump shipments tumbled by one third in the four years from 1978 to 1982. When the gas moratorium was lifted soon after, the natural gas utilities had to invest to get gas service to the newest construction areas. Competition continues to be fierce, and the North American heat pump market continues to grow at a slow but steady pace. (Internet source 28)

The biggest improvement in recent years has been to use of higher efficiency scroll compressors in many lines of heat pumps and air conditioners. Also, variable speed drives for compressors and fans help achieve better part load efficiencies. These are utilised in some of the higher end equipment. Most individual measures to improve efficiency are small, but they add up. There are research projects being undertaken by the industry’s 21st Century Research program that show promise of adding efficiency, reliability and comfort.

Financial incentive schemes have been introduced by several electric utilities in the U.S. encouraging house owners to use groundwater heat pumps for space cooling/heating purposes and thus, reduce the peak loads on their electric systems. (Fridleifsson, 1998) The Geothermal Heat Pump Consortium (GHPC), a partnership of government, industry and over 240 utilities, has shown that an important first step to sustainability of the geothermal heat pump industry is a commitment from government to support market development and to build alliances and initiatives within a coalition of stakeholders. The GHPC has established the following goals:

- To reduce annual greenhouse gas emissions by 1.5 Mt annually by the year 2005.

- To increase annual unit sales of geothermal heat pump systems from 58,000 to 400,000 by the year 2005.
- To help the technology reach sufficient market penetration that it becomes self-sustaining without further help or incentives from government or utility sources.

To that end, the GHPS established a 6-year program. Until March 2001, the GHPC has invested more than $50 million to develop the geothermal heat pump market. (Internet sources 29 and 30)

6.3. International collaboration and targets

Since its inception, the primary purpose of IEA's Heat Pump Program (HPP) has been to foster continued and increased deployment of the heat pump technology to achieve improved energy efficiency and environmental benefits. Consequently, the Programme is established and designed to be a link between the R&D community and the market, a body that should facilitate a higher degree of market penetration for heat pumps. The basic idea behind the HPP is that different countries face many common challenges, and that these challenges are most effectively solved through international collaboration and pooling of resources. (IEA Heat Pump Centre Newsletter, 2002)

Under the auspices of the IEA the so-called a number of Annexes are executed, e.g. Annex 25, Annex 26, and Annex 27. Annex 25 covers 'Year-round Residential Space Conditioning and Comfort Control Using Heat Pumps'. After three years of operation, Annex 25 has been finalised. Annex 26 covers 'Advanced Supermarket Refrigeration/Heat Recovery Systems'. Countries involved are: the USA, Canada, Denmark, Sweden, and the UK. The total value of the research work under Annex 26 is approximately $5 million. This represents a leveraging of each participant's funds of up to 10:1. Therefore, the total R&D budget from the IEA countries involved amounts to approximately $50 million.

The recently finalised Annex 27 covered 'Selected Issues on CO_2 as Working Fluid in Compression Systems'. The main objective of this Annex was to bring CO_2 technology closer to commercialisation, by adding critical issues of both a basic and applied character. It is important to involve industry, especially manufacturers, as well as research organisations. The budgets of Annex 25 and 27 are unknown. Annex 28 deals with 'Test Procedure and Seasonal Performance Calculation for Residential Heat Pumps with Combined Space Heating and Domestic Water Heating' and is in the stage of start-up. (IEA, 2003)

In an effort to contribute substantially to the increased use of renewable energies, to energy saving and to CO_2 emission reduction in Europe, the European Heat Pump Association (EHPA) intends to double the number of heat pumps that are expected to be installed in the year 2010, i.e. roughly 7.3 million (Internet source 31).

6.4. Summary of sales and R&D data

Figure 6-23 and Table 6-6 present annual sales of heat pumps in a number of countries. Sales of heat pumps in Europe are estimated at close to 600,000/a, in Japan at 2,000/a, in Canada at 4,000/a, and in the U.S. at 58,000/a. Global annual sales could amount to 660,000 or more.

Figure 6-23: Sales of heat pumps in Europe and Japan (indicative)

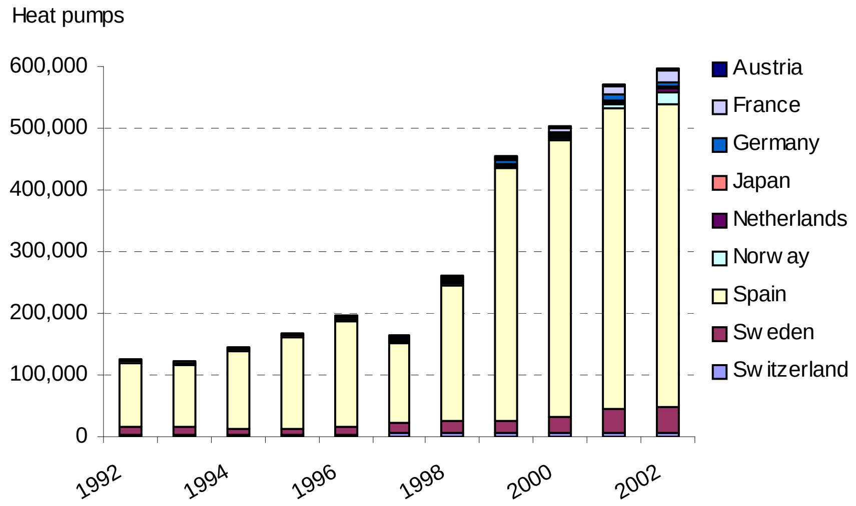


Table 6-6: (Indicative) sales of heat pumps in Europe and Japan (1992-2003)

	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Austria[1]	850	1125	1300	1450	1700	1675	1825	1850	2200	2980	2980	3500
France	1500	1500	1500	1500	1500	1600	3200	5200	6800	14200	20000	
Germany[1]	850	900	900	1200	2310	3580	4367	4717	5737	8213	8315	13521
Japan[2]	250	275	275	700	775	900	1050	1250	1500	1850	2250	
Netherlands	721	721	721	721	2543	2381	3061	2818	2650	3327	5512	
Norway	1750	1000	1350	1275	1300	2100	2250	2650	3395	6300	21300	56000
Spain[2]	103000	102000	124667	147333	170000	130000	220000	410000	450000	490000	490000	490000
Sweden	15200	13250	10040	8900	12300	17100	18400	20100	24250	36700	39825	49000
Switzerland	2260	2420	3309	4160	4207	5225	6155	6160	6943	7168	7554	8677
Total	126381	123191	144062	167239	196635	164561	260308	454745	503475	570738	597736	

[1] Heating-only heat pumps.

[2] Sales in Japan were extrapolated after 1996; sales in Spain were assumed to remain stable after 2001.

Figure 6-23 and Table 6-6 also show the recovery of international heat pump market during the nineties, when sales almost quintupled from 126,000 in 1992 to 598,000 in 2002.

Table 6-7 shows that the total number of installed heat pumps in the regions considered – Western Europe, Japan, and North America – could amount to approximately 4.5 million.

Table 6-7: Indicative numbers of installed heat pumps (2002) for selected countries

	Ground-source heat pumps	Air-to-water/air-to-air heat pumps	Total
Austria	27,200	137,800	165,000
Canada	30,000	-	30,000
France	500	247,500	248,000
Germany	21,200	87,200	108,400
Japan	300	12,500	12,800
Netherlands	1,200	32,000	33,200
Norway	58,300	-	58,300
Spain	-	3,000,000	3,000,000
Sweden	73,500	231,000	304,500
Switzerland	25,400	60,000	85,400
United States	450,000	-	450,000
Total	687,600	3,808,000	4,495,600

The Electric Power Research Institute (EPRI) estimated that 800,000 heat pump units (of all kinds) were installed annually in 1988, 25,000 of which geothermal heat pumps (Lund, 1990). Table 6-8 gives an overview of the global development of geothermal heat pumps in 2000 based on (Lund, 2003a) and (Internet source 8).

Table 6-8: Worldwide geothermal heat pump installations in 2000

country	capacity [MW_{th}]	energy produced [TJ/a]	[GWh/a]	heat pump installations	equivalents of demand of 12
Australia	24	57.6	16	2,000	2,000
Austria	228	1,094	303.9	19,000	19,000
Bulgaria	13.3	162	45	16	1,108
Canada	360	891	247.5	30,000	30,000
Czech Republic	8	38.2	10.6	390	663
Denmark	3	20.8	5.8	250	250
Finland	80.5	484	134.4	10,000	6,708
France	48	255	70.8	120	4,000
Germany	344	1,149	319.2	18,000	28,667
Greece	0.4	3.1	0.9	3	33
Hungary	3.8	20.2	5.6	317	317
Iceland	4	20	5.6	3	333
Italy	1.2	6.4	1.8	100	100
Japan	3.9	64	17.8	323	323
Lithuania	21	598.8	166.3	13	1,750
Netherlands	10.8	57.4	15.9	900	900
Norway	6	31.9	8.9	500	500
Russia	1.2	11.5	3.2	100	100
Poland	26.2	108.3	30.1	4,000	2,183
Serbia	6	40	11.1	500	500
Slovak Republic	1.4	12.1	3.4	8	117
Slovenia	2.6	46.8	13	63	217
Sweden	377	4,128	1,146.70	55,000	31,417
Switzerland[1]	300	1,962	545	21,000	25,000
Turkey	0.5	4	1.1	23	43
UK	0.6	2.7	0.8	49	53
USA	4800	12,000	3,333.30	350,000	400,000
Total	6,675.40	23,268.80	6,463.60	512,678	556,282

[1] *Internet source 8.*

Table 6-9 shows a few data with regard to government expenditures on R&D with regard to heat pumps, based on the preceding paragraphs on IEA countries and the IEA Heat Pump program.

Table 6-9: Government expenditures on R&D with regard to heat pumps

	1974	1995	1996	1997	1998	1999	2000	2001	2002	2003
France			300 k€							
Germany		€ 7.5 million (1974-1998)								
Switzerland								€1 mln		
IEA Annex 26									(€ 50 mln)	

The budget for IEA Annex 26 is shown between brackets as the R&D involved is related to ‘Advanced Supermarket Refrigeration/Heat Recovery Systems’, which is not identical to R&D on heat pumps.

7. Condensing Boilers

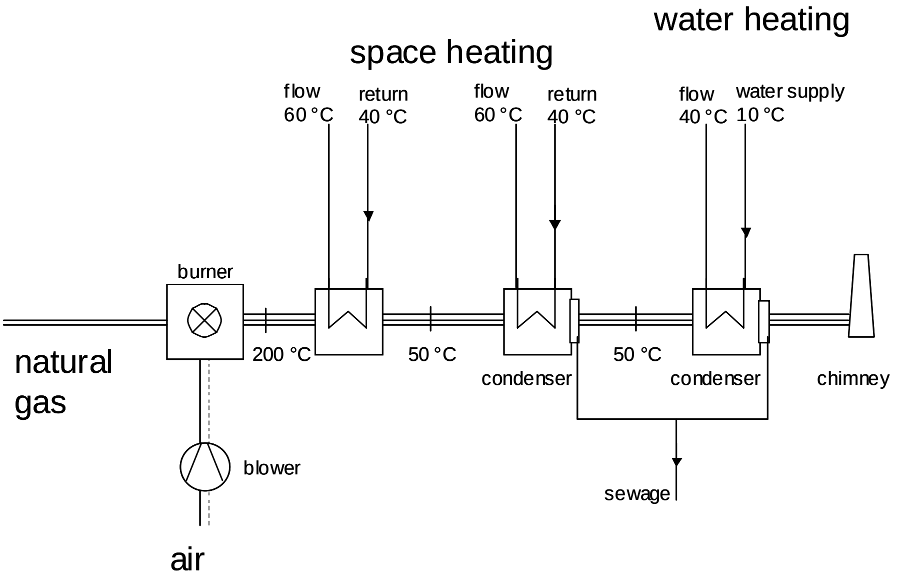
7.1. Technology description

Saving primary energy has been energy technology´s main purpose for the last decades. A very significant part in reaching this target can be played by condensing boilers. Condensing boilers are an evolution of conventional boiler systems, with additional heat production by condensation of the steam fraction from the flue gas stream. Thus, the utilisation of the fuel´s energy content can exceed the lower heating value LHV, which is a limit to conventional systems. This means efficiency rates higher than 100 % (relative to the LHV) are possible, as condensing boilers are capable of also utilising the enthalpy of evaporation concealed in the steam fraction of the flue gas by condensing. Using natural gas as a fuel 10 to 11 percents of efficiency can be gained by a condensing boiler compared to a non-condensing system; using oil the advantage over conventional systems is just 5.5 to 6 percents - the difference in potential usually makes gas-fuelled condensing boilers the more attractive alternative.

Further advantages of condensing boiler technology comprise fuel variability (either oil or/and different kinds of gas), low space demand, low emissions, low noise, high degree of modulation, and good cost/performance ratio due to high degrees of systems integration of burners and boilers. Besides, the lower flow rates allow the integration of downsized fittings, thus reducing investment costs. In combination with the savings from lower fuel consumption a high economic efficiency can be obtained, including short payback periods.

Figure 7-1 gives an overview of a condensing boiler`s main components and their functions.

Figure 7-1: Scheme of a gas-fuelled condensing boiler



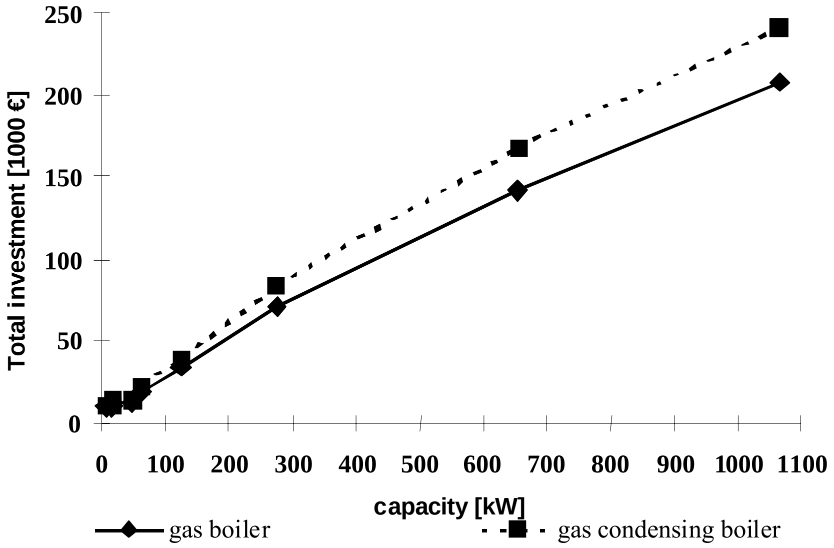
Condensing boilers primarily were designed for large systems with capacities of several hundred kW to meet with industrial demands. Meanwhile, suitable capacities for residential space heating have been offered.

From their market introduction in the early 1980s, condensing boilers have continuously made their way towards becoming a considerable factor in the heat supply market. In 2002 condensing boilers for residential space heating have reached market shares of 89 % of all gas boilers for residential space heating in the Netherlands (1996: 56 %), 62 % in Germany (1996: 18 %), 13 % in the UK (1996: 4 %), 3 % in Italy, 44 % in Austria, 16 % in Denmark, and 21 % in Belgium (Pfannstiel, 2003; Haug et al, 1998). However, the statistics is led by Switzerland, where condensing boilers in 2002 have made 100 % of all gas boilers sold for residential space heating (Pfannstiel, 2003).

7.2. Cost and capacity development

A first examination of condensing boilers` investment costs has been given by (Blesl, 2002) (see Figure 7-2), with a comparison of investment costs for condensing boilers and conventional systems over capacity.

Figure 7-2: Comparing investment costs of low temperature gas boilers and gas-fuelled condensing boilers over capacity, construction of district heat stations included (Blesl 2002)



Further cost data are available through ewu for the years 1992, 1994, and 1999, as illustrated by Figure 7-3. Additionally, the cumulative capacities of condensing boilers in the German market are depicted in Figure 7-4.

Figure 7-3: Specific investment costs of condensing boilers in Germany for different years (ewu 1992, 1994, 1999)

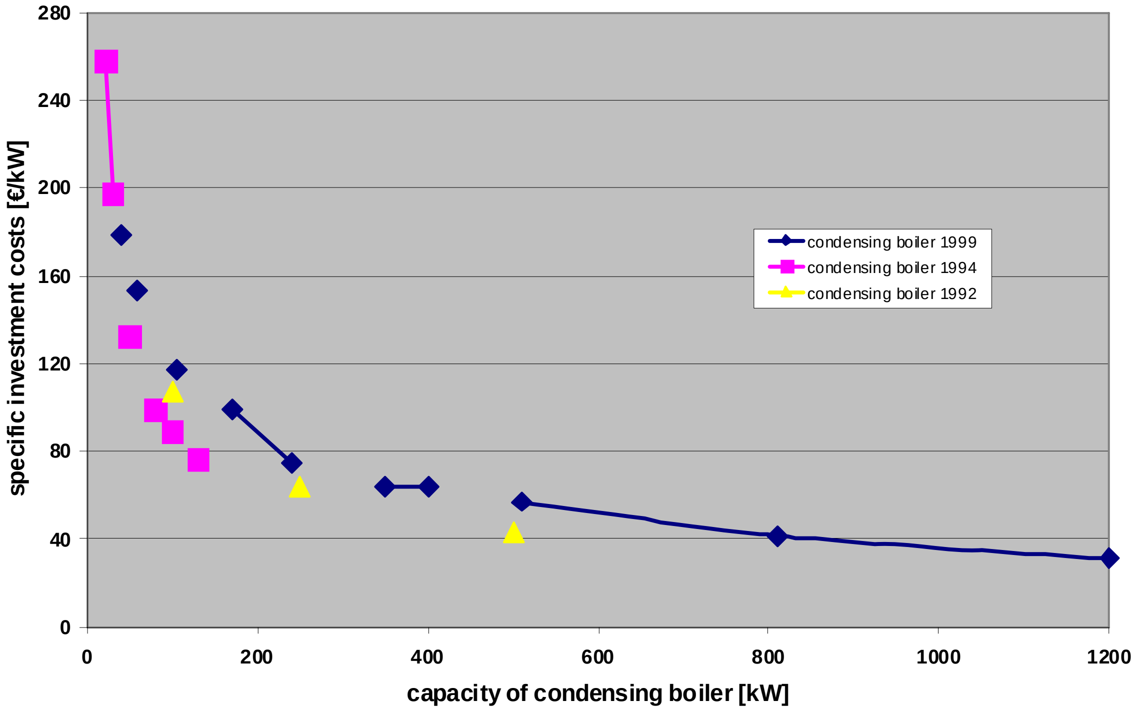
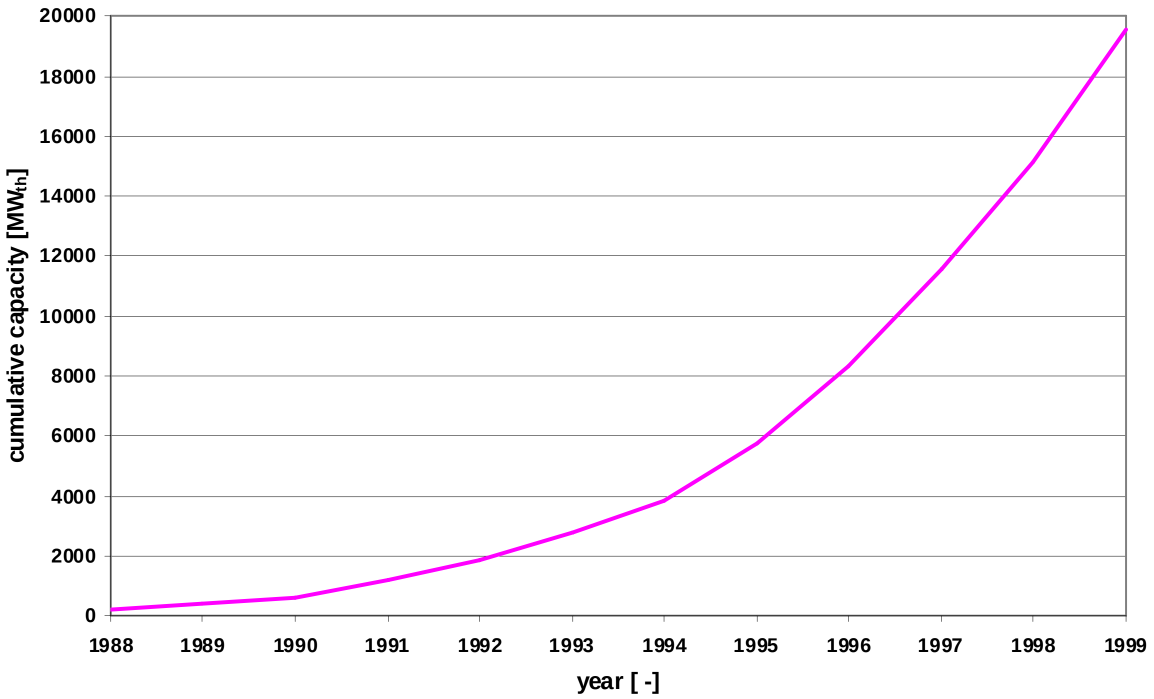
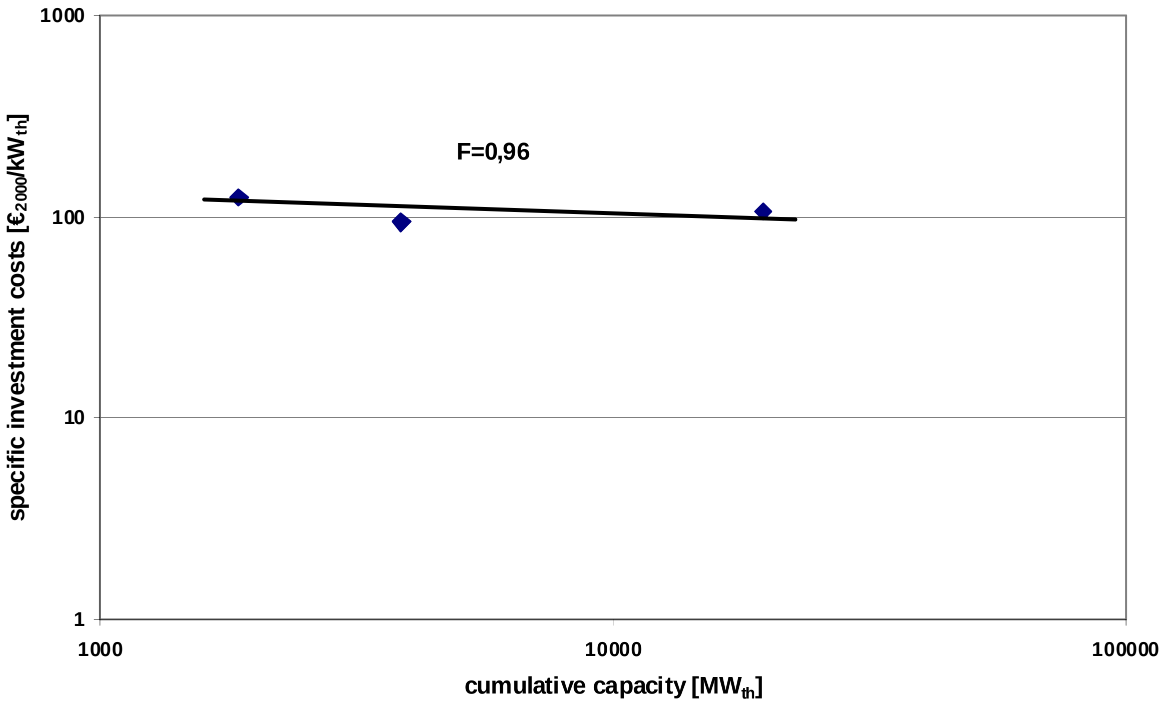


Figure 7-4: Cumulative capacity of condensing boilers installed in Germany 1988-1999 (Beckervordersandforth, 2001)



With the information delivered by the two diagrams a learning curve can be constructed (see Figure 7-5).

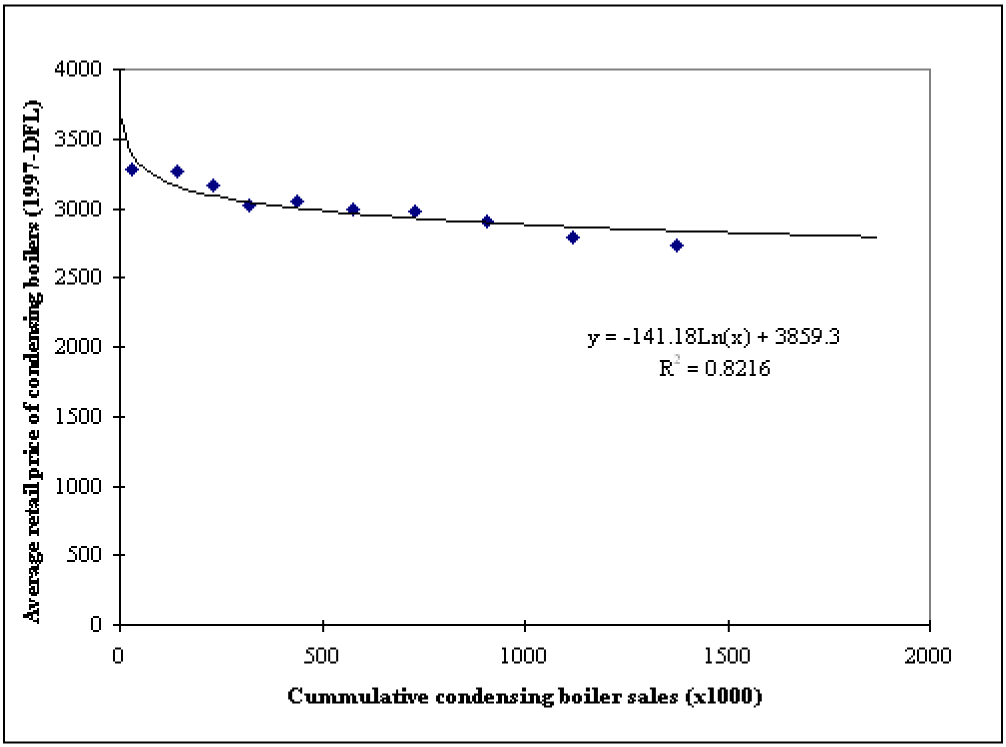
Figure 7-5: Inflation-adjusted learning curve for the German condensing boiler market 1992-1999



For the German market the learning factor of condensing boilers is 0,96.

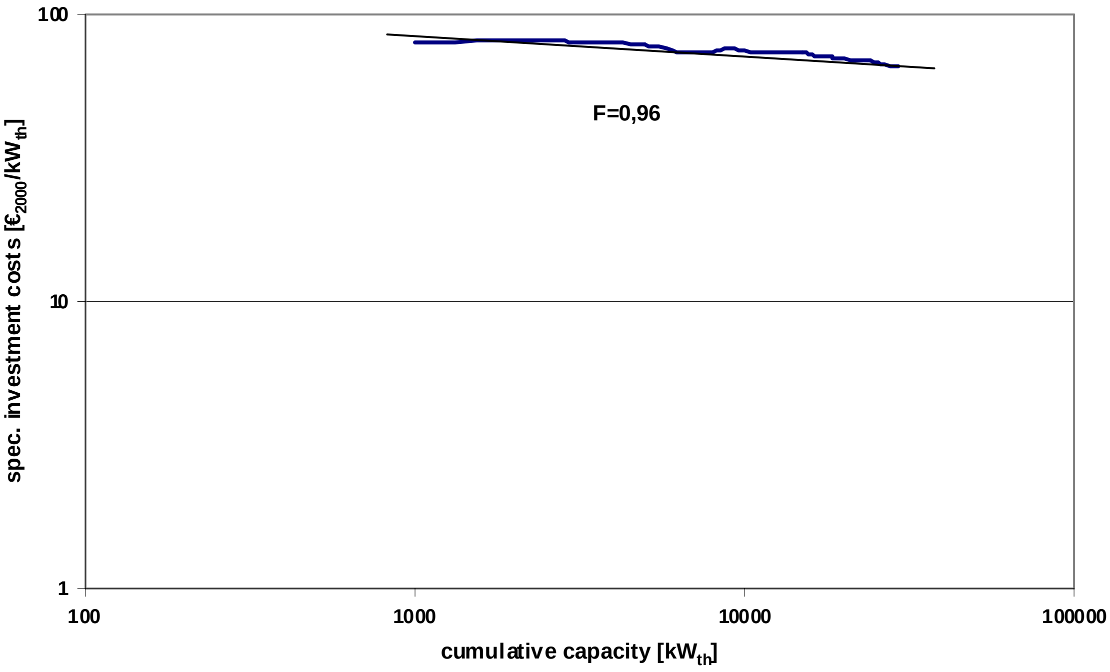
Haug et al. 1998 have dealt with the development of investment costs of condensing boilers over cumulative sales for several European markets. For the Dutch market (see Figure 7-6) there was sufficient data available to examine learning effects.

Figure 7-6: Development of investment costs of condensing boilers in the Dutch market over cumulative sales for capacities between 15 and 25 kW (Haug et al., 1998)



The learning curve for the Netherlands is shown in Figure 7-7.

Figure 7-7: Inflation-adjusted learning curve of condensing boilers in the Netherlands 1983-1997



Exactly like for the German market, the learning factor for the Netherlands is 0,96. This is a pretty small learning factor that proves that the condensing boiler is a mature and established technology with very little opportunities for further cost reductions left unless by a continuous widening of production.

A first comparative overview of operational costs of low temperature gas boilers and condensing boilers is given by Table 7-1.

Table 7-1: Overview of basic data for low temperature gas boilers and gas condensing boilers

		low temperature gas boilers		gas condensing boilers	
capacity	[kW_{th}]	12	60	12	60
annual use efficiency	[%]	90	89	96	94
spec. investment costs	[€/(MWh_{th})]	345	165	445	193
spec. fixed operational costs	[€/(MWh_{th})]	17	8	17	8
spec. other variable costs	[€/(MWh_{th})]	1,15	1,05	1.1	1.14

It becomes obvious that conventional low temperature gas boilers have lower specific investment costs than gas-fired condensing boilers. Instead, the annual use efficiencies of condensing boilers are higher. Whereas the fixed operational costs (e.g. for maintenance) are the same for both types of boilers, the spec. other variable costs of condensing boilers can be 4,3 % lower for small capacities (12 kWth), due to better fuel utilisation. For larger capacities (60 kW_{th}) with a lower annual use efficiency (in compare to the smaller-sized condensing boiler), spec. other variable costs can be higher than for conventional boilers.

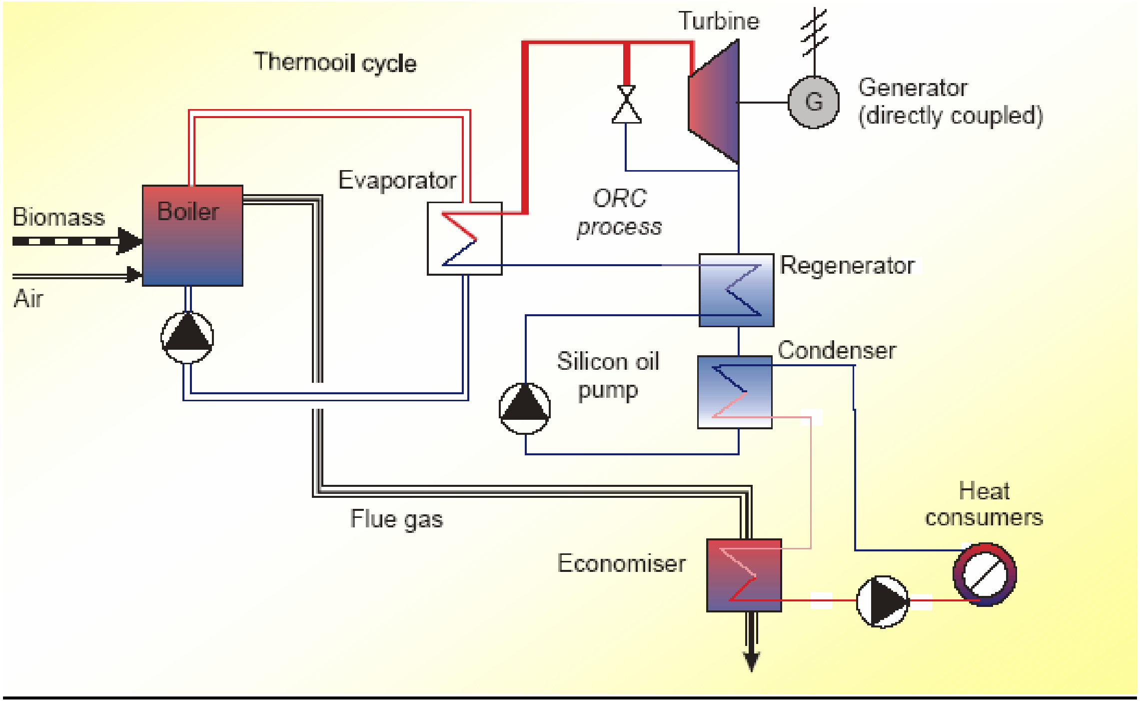
8. Organic Rankine Cycle

8.1. Technology description

Organic Rankine Cycle (ORC) is a rather new technology for the production of heat and electricity. ORC plants are particularly suitable for the utilisation of heat from geothermal sources or biomass combustion. ORC´s technical principle resembles the conventional Rankine process as used for electricity production by steam turbines. The basic difference is the application of liquid (organic) hydrocarbons, like toluene, isopentane, isooctane or polysiloxane oil as a working fluid, instead of water. The respective plant layouts are accordingly similar.

With biomass fed ORC plants, biomass is combusted with air supply in a boiler. The heat produced thereby is transferred to a thermo-oil cycle by a heat exchanger. Another heat exchanger evaporates the working fluid in the ORC circulation system to drive the turbine. A generator connected to the turbine turns the turbine´s mechanical energy into electricity. The heat left in the ORC circulation system is transferred to a heat consumer cycle by a condenser, e.g. for a district heating application. This cycle also takes up the waste heat from the flue gas of the combustion, thus enhancing thermal overall efficiency. The basic process of a (biomass-fueled) ORC plant is shown in Figure 8-1. An advanced version of an ORC plant operating with combustion air preheated by the flue gas is depicted in Figure 8-2.

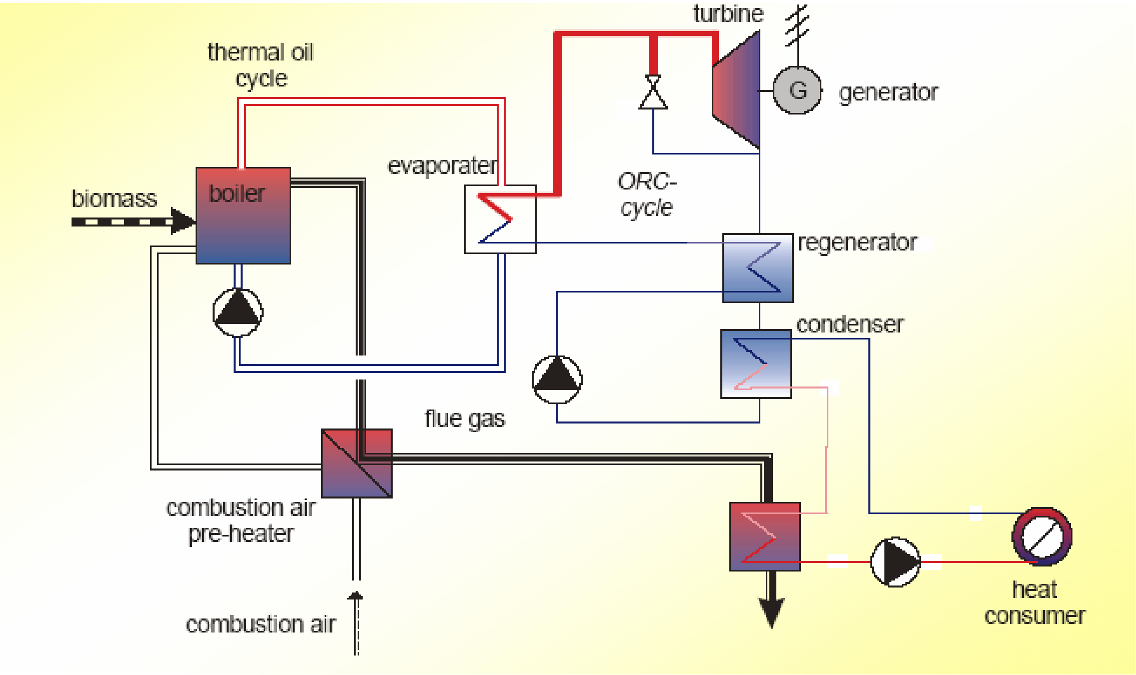
Figure 8-1: Process scheme of a biomass-fueled ORC plant (Obernberger, 2003)



When utilising geothermal heat in an ORC plant, the thermo-oil cycle is dispensed with, so that the hot water from the well is directly used for the evaporation of the organic working fluid. The rest of the layout is similar to that of biomass fed plants, yet without the additional components for the recovery of the heat from the flue gases.

One of the advantages of the ORC concept, compared to a steam based Rankine process, is the lower boiling temperature of the organic working fluids. Hence heat of a temperature level even below 300 °C can be used for electricity production. Turbine efficiency is 85 % with good controllability and excellent properties of the turbine under part load (operating range 10-100 %) (Obernberger, Hammerschmied,1999). The turbine has a very low start-up period enabling flexible temporal operation. Overall efficiency including waste heat utilisation can be from 70 up to 105 %, if a flue gas cooling system is applied to condense the steam fractions of the flue gases. By choosing an appropriate working fluid, the process can be adjusted to the conditions both on the hot and the cold side of the plant, thus achieving the maximum efficiency. The plants can be operated in a completely automated mode, and ORC technology already has positive operational records. Moreover, ORC plants have very low maintenance costs.

Figure 8-2: Advanced ORC plant with combustion air pre-heater (Obernberger, 2003)



The essential disadvantages of ORC plants concern their high demand of heat exchanger surface if thermo-oil is involved in the process and the fact that there is only a heat-conducted operation mode possible. Beside these points, ORC plants need high full load operation periods of 4000-6000 hours per year for cost effectiveness, and their electrical efficiency of 13-18 % (relative to the energy content of the fuel) is very low. The electricity-heat ratio of ORC plants is 0,23, which is also very low compared to competitive power generating technologies. Current overall investment costs are 7475 €/kWel (reference: Admont ORC plant, Austria), which is severalfold higher than investment costs of conventional power plants. Using geothermal sources has specific investment costs of 2529 €/kWel (Kaltschmitt et al., 2003) with a range of electrical efficiency between 4 and 13 %, relative to the heat content of the hot water pumped from the ground. Most significant technical data, classified by different sources of heat, is summarised in Table 8-1.

Table 8-1: Basic data on the utilisation of heat from different sources in ORC plants

	heat source		
	geothermia	biomass combustion	industrial processes (1985)
range of capacities available [kW$_e$]	100-1200	100-2000	100-10000
Electrical efficiency [%]	4-13	13-18	15
spec. overall investment costs [€/kW$_e$] (reference value)	2529 (850 kW$_e$)	7765 (400 kW$_e$)	1235-2556 (960 kW$_e$)
thermal range of heat source [°C]	100-240	max. 1100	100-400

8.2. Current capacity

Currently plant capacities between 100 kWe and 1,5 MWe are available. In Germany, nine plants with a total of 6500 kWe are operating (reference year 2004) (Gaderer, 2002; Mrowald, 1999; Kohlbach, 2004) plus one 1500 kWe plant being under construction. Throughout Europe there are another 22 plants with a total of 22100 kWe in service or under construction (see Table 8-2).

Table 8-2: ORC plants in Europe (Gaderer, 2002; Mrowald, 1999; Kohlbach, 2004; Turboden, 2004)

country/location	capacity [kW_e]	commissioning year	comments
Germany			
Lengfurt	1200	1999	utilisation of industrial waste heat from cement production
Sauerlach	480	2001	district heating; overall investment costs 8900 k€
Weimar	500	2002	
Friedland	500	2001	
Wurzbach	400	2001	
Lobenstein	500	unknown	
Ostfildern	1000	2002	wood chip combustion as heat source; overall investment costs 5202 k€, investment costs ORC 1607 k€
Hengersberg	1500	under construction	
Neckarsulm	1000	2002	district heating; investment costs ORC 1400 k€, overall investment costs 6000 k€
Ploessberg	1100	2003	wood combustion; heat supply for the drying process of a pellet factory
Austria			
Admont	400	1998	overall investment costs 3200 k€
Lienz	1000	2002	district heating: investment costs ORC 1360 k€
Fussach	1000	2001	incl. absorption chiller (1350 k€), CHP 6140 k€
Seyring (Vienna)	1000	2002	incl. absorption chiller

Besides the heat sources mentioned, ORC plants can also be operated using waste heat from industrial processes. For example, the ORC plant at Lengfurt, Germany, is supplied with heat from cement production (about 275 °C) (Mrowald, 1999).

8.3. Investment Costs and Learning Curve Approach

Investment costs of the most significant ORC components are shown in Table 8-3. Compared to other technologies of large-scale heat production, ORC plants result to be quite expensive. Therefore the operation of ORC plants is still depending on public subsidies.

Investment costs of a technology do not grow proportionally with plant capacity. The capacity-related investment costs of a technology though can be calculated by the formula

$$I_1 = \sum_{j=1}^{J} i_{j,0} \cdot \left(\frac{c_{j,1}}{c_{j,0}} \right)^{n_j}$$

with,

I= investment costs of plant,
i= investment costs of component,
J=number of components
c=capacity
n= exponent of degression
index 0: data of base capacity
index 1: plant/component to be examined

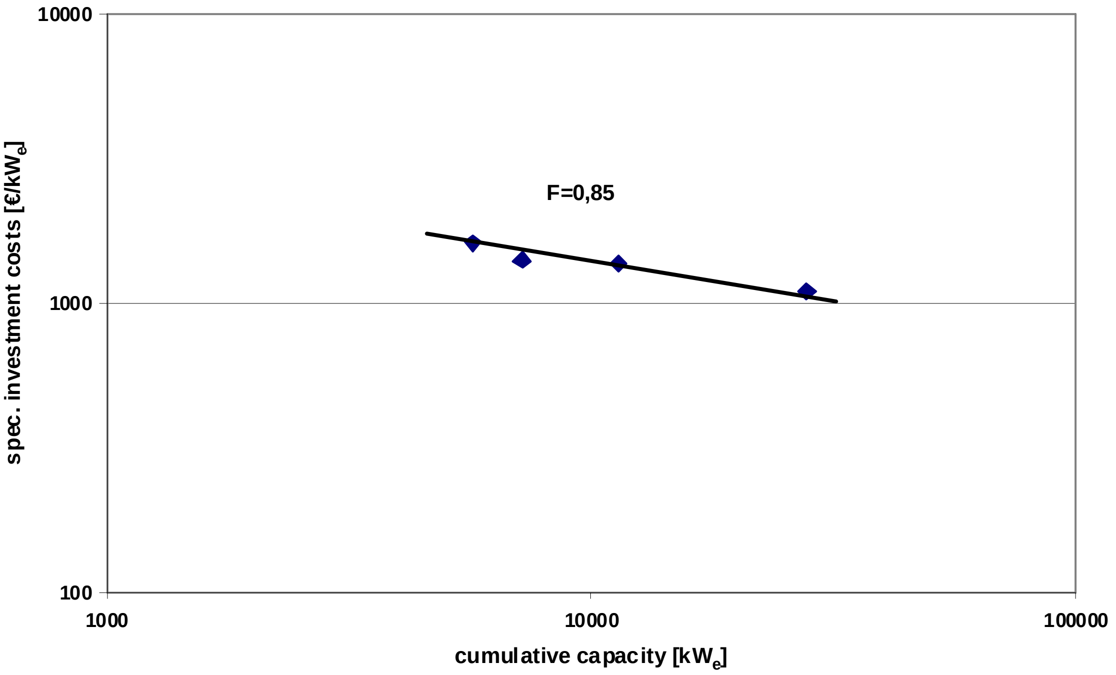
Table 8-3: Current investment costs for ORC-plant components

Component	Base capacity	investment costs [€]	exponent of degression
thermo-oil boiler incl. ash rempoval and control system	5000 kW_{th}	784000	0,48
fuel supply incl. silo	5000 kW_{th}	52000	1,40
electrostatic flue gas filter	5000 kW_{th}	165000	0,34
ORC module incl. generator and control system	1200 kW_e	1250000	0,68

As there is quasi just one manufacturer of ORC core technology in the market, it is no use to examine European ORC applications split up into national markets. Instead, the European ORC market is regarded as one.

The learning curve of European ORC technology is shown in Figure 8-3. As the data for this curve come from different countries (Germany and Austria) no inflation-adjustment could be performed.

Figure 8-3: Learning curve for ORC modules (European market)



The learning factor for ORC modules is currently 0,85, which is quite typical for this stage of the technology, as there´s no serial production of ORC modules so far. For the calculation of the overall investment costs it is important to know that the ORC module is just one part of the entire plant, as there are a lot of other components required, depending on the plant´s purpose (e. g. district heating supply) and its energy source (for instance geothermia or combustion of different kinds of waste materials or fuels) utilized. Some of the other components that are vital to the operation of an ORC plant have already been produced in serial production (e. g. the boilers, pumps, heat exchangers), some have to be manufactured in single production without a chance for serial production (buildings, fuel preparation). For these parts neither a general or an essential cost reduction should be expected even for an increased cumulative capacity.

8.4. Current R&D issues

R&D activities in ORC technology are focussing on the quest for new organic working fluids and new energy sources, especially from different kinds of industrial processes. In the geothermal area the number of plants projected is steadily increasing. Besides, the manufacturers of ORC modules are eager to develop and install serial production facilities in order to raise the output and cut down production costs.

9. Methodology for Development of an R&D Database for selected non-power technologies

The development of a database containing data of non-power technologies is an essential part of the SAPIENTIA project. The characterization should be such that both a direct implementation of the technology is feasible, as well as an implementation in which the technology is described as a (part of a cluster of a) learning technology. What is more, the formalism developed in the preceding project, SAPIENT, of a two-learning characterization of technologies is to be deployed to the new technologies as well. This requires that not only present day data and (expert guesses of) future developments are gathered, but also historical data is presented from which the parameters of the two-learning mechanism can be deduced. In this Chapter we will discuss which technologies have been chosen, and what data has been collected for these technologies. In the Annexes, data sheets for the different technologies are included.

9.1. Choice of technologies

In the SAPIENT project a description of technologies using a two-factor learning mechanism was developed. The technologies in the models used were mainly power-technologies. One of the aims of the present project is to extend the formalism to a selected set of non-power technologies. The selection should on the one hand be sufficiently broad to show that the idea of learning technologies may be applied to many different sectors. However, on the other hand the selection should be such that reliable data can be gathered, or that an alternative formalism may be developed in which proxies may be used to estimate the relevant parameters for the two-factor learning curve.

The list of technologies considered in SAPIENTIA are given in the table below. To show that indeed a broad range of sectors is to be included in the analysis, the table also shows the sectors in which the technologies are applied.

Table 9-1: Choice of technologies for the SAPIENTIA project

Technology	Power related	Power and heat	Industry	Commercial	Domestic	Transport
Fuel cells		x	x	x	x	x
Condensing boilers		x	x	x	x	
Conventional boiler		x	x	x	x	
Heat pump		x	x	x	x	
ORC		x	x			
Liquefaction	x	x				x
Compression	x					x
Electrolysis $_{H2}$	x					x
Gas steam reforming $_{H2}$	x					
Coal partial oxidation $_{H2}$	x					
Biomass pyrolysis H_2	x					
Solar thermal HTS electrolysis $_{H2}$	x					
Heat insulation			x	x	x	
ICE, Otto						x
ICE, Diesel						x
Electric engine			x			x
Capture of CO_2	x					
Storage of CO_2	x					

From the table it is clear that we have chosen to include some technologies that are also used in the power sector. The main reason for choosing these is that they are applied in other sectors. The choice is in line with the objective of the project also to study spill over effects.

9.2. Data gathered for the selected technologies

It is clear that the data gathering is essential to reaching some of the objectives of the SAPIENTIA project. In particular, the extension of the models to include non-power technologies can only be commenced if and when sufficient data is gathered to enable some form of estimation for the two-factor learning curves. In Table 9-2 an overview of data gathered for the selected technologies is given.

Table 9-2: Status of data

Technology	Present data		Future guesses		Historic data	
	Price	Technical	Price	Technical	Price, Capacity	R&D
Fuel cells	yes	yes	yes	yes	short history	SAPIENT
Condensing boilers	yes	yes	yes	yes	figures	estimate
Conventional boiler	yes	yes	yes	yes	no	no
Heat pump	yes	yes	(ECN)	(ECN)	no	no
ORC	yes	yes	no	no	no	no
Liquefaction	yes	yes	yes	yes	yes	yes
Compression	no	no	no	no	no	no
Electrolysis H_2	yes	yes	yes	yes	short history	aggregate
Gas steam reforming $_{H2}$	yes	yes	yes	yes	short history	aggregate
Coal partial oxidation $_{H2}$	yes	yes	yes	yes	short history	aggregate
Biomass pyrolysis H_2	yes	yes	yes	yes	short history	aggregate
Solar thermal HTS electrolysis H_2	yes	yes	yes	yes	short history	aggregate
Heat insulation	(ECN)	yes	yes	yes	windows	no
ICE, Otto	yes	yes	yes	yes	yes	yes
ICE, Diesel	yes	yes	yes	yes	yes	yes
Electric engine	yes	yes	yes	yes	yes	yes
Capture of CO_2	yes	yes	yes	yes	no	no
Storage of CO_2	yes	yes	yes	yes	no	no

As a first note to the table, it can be remarked that current data on selected technologies is available for all but one technology (compression of gasses, such as H_2), both on price levels as well as on key technological data such as efficiencies. This can be seen from the low number of technologies with a red marked ‘no’ in the relevant columns in the table. The situation is almost as favourable for the (expert guesses of) future technological characteristics for the selected technologies, where only ORC in addition to compression shows a lack of data.

The real problem in the data turns out to be reliable historical data on technologies, where only for automotive technologies some extended time series are available. The situation is even worse for R&D-spending, most particularly that of business. It can be seen that for many technologies, hardly any data on the R&D expenditures has been gathered. It is furthermore noteworthy that for those technologies for which R&D expenditures have been found, in many cases the data is on an aggregate level, i.e. does not give information about specific technologies. Given the problems encountered so far, it is unrealistic to assume that one may use a more detailed level of technologies. This was initially suggested, particularly for the fuel cells.

From the efforts in the SAPIENTIA project, we can conclude that for non-power technologies the knowledge on key statistics needed for a dynamical description of technologies using learning is quite unfavourable. This is a rather disappointing statement, particularly in view of previous experience from the SAPIENT project (where the effects of learning for power technologies was investigated). There are several reasons for this diverging conclusion for non-power technologies :

- A database similar to the (public) R&D expenditure database of the IEA is currently lacking for the selected technologies,
- Many of the technologies are in a very early stage of development, so that

    - In many cases, there is no data on installed capacities, a key statistic even for the relatively simple framework of learning-by-doing,
    - Existing data is of strategic value and hence not readily surrendered for public use,
    - Firms involved in developing the selected technologies are starters, and may prove hard to identify, rendering the collection of business R&D extremely difficult.
- Even for established technologies, R&D data on specific technologies may prove hard to get due to strategic value of such data; an example is provided by the automotive industry. Here, a formalism for disaggregating data using proxies can be developed.

One might be tempted to use generic values, but for the present project such generic values would be useless, since we are interested in the specific behaviour of the technologies under consideration.

9.3. R&D showcase: the automotive industry

As noted in the previous paragraph, data on R&D is hard to obtain, particularly when considering specific technological options. For some of the technologies selected in the project the data may be harder to come by than for other technologies, particularly for individual technologies. In such cases, when data on aggregated technologies is available, auxiliary data (or proxies) may be used to de-convolute the to the level of individual technologies. To show the most likely approach to yield data, we have selected a relatively easy set of technologies as a showcase: the automotive technologies. The main advantages of these technologies are:

- A small number of companies that dominate the market
- A strong pressure on companies to show their efforts to improve the (environmental) performance of the technologies
- Easy access to (recent) company data
- Spearhead development area for governmental research

To gather data on the expenditures on research and development, both from companies and through government, we have used the following scheme:

- Identify the major companies involved in R&D
- Gather annual reports from these companies, if these contain explicit figures on R&D
- Build a data set containing as much data on R&D spending as possible
- Gather auxillary data: patents and sales numbers of specific technologies
- Combine the above to estimate the R&D expenditure through companies

The result is a complex set of data. This complex set should be reduced to a simple set that contains technology, sales, capacity, business R&D, and government R&D. It may be interesting to provide sales and capacities on a regional level, since these may be data directly relevant to the models used in SAPIENTIA.

So far, we have been able to find data on a global scale, which is not surprising given the fact that automobile companies are mainly international corporations. The number of independent producers is quite limited, as the result of substantial mergers in the past. This concentration appears to continue until this very day, but the focus has shifted from full-blown mergers to enhanced cooperation. As to the data collection efforts, the effects of these recent concentration activities for now can be ignored, but the full-blown mergers are likely to have a profound effect on the data available. As we extract data on sales and particularly on business R&D from the annual reports, it is important to know to what extend merging companies are included in the historical figures of the new company.

For the automotive industry, there appear to be twelve major companies. It should be noted that these companies in many cases are the results of mergers in the recent or more distant past. This results in a limited history of the companies, and a limited availability of annual reports. Furthermore, in some cases mergers have occurred in the very recent past. This also limits the applicability of data in the annual reports.

For the twelve major companies, a varying historical record is available in the annual reports. The variation may be either in the number of years for which data can be found, or in the amount of information provided on the R&D expenditures, or even both. Thus, we obtain a data set on sales and business R&D expenditures containing several ‘holes’. These holes can be filled when additional assumptions are made on the behaviour of companies. For example, if we assume equal behaviour for all companies, an average value may be inserted (imputed) for a missing value. Other options are to assume linear investment trends within a company, or investment trends within a year, or even a combination of the two.

Using the data mentioned in the previous paragraphs, we have constructed a data set for twelve companies spanning twelve years. None of the companies provide data for the full set. Nevertheless, from the data that is available, some striking features can be found. First of all, when expressing the R&D budget as percentage of sales, the various companies spend between 2.1% up to 6.5%, averaged over the years for which data is available. From the data gathered, it is clear that firm size in terms of sales, or geographical origin cannot serve as an auxiliary variable for estimation of the R&D budget. All one can do is estimating the budget for a specific firm on the basis of data available for that particular firm. Thus the sector-average of the R&D spending as percentage of sales budget can be estimated on the basis of available data. From this we find a sector average of 4.6%. On the basis of the data, no reliable estimate can be give for the time-dependence of the percentage.

From the previous paragraph it should be clear that at present R&D dynamics can not be established on the basis of business R&D data alone. Furthermore, in many cases government R&D expenditures are linked to business R&D, e.g. in the case of spending by the federal government in the United States. As a result, the government spending are also not very practical as variable introducing R&D dynamics. The only remaining possible data mentioned in the beginning of the section would be to use patent data, or sales numbers of specific technological options. As the latter are a proxy for learning by doing (see below), we opt for patent data.

Gathering the patent data involves the use of the major companies identified in the first step of the data collection. Using the patent database of the European Patent Office (available at http://ep.espacenet.com) we first search for all patents posted by the selected companies. Next, we look for specific patents, either dealing with internal combustion engines, electric vehicles or fuel cell vehicles. The result is a data set containing both the absolute and the relative amount of patents. It should be noted that the data set of the European Patent office contains both national and international data. Therefore, one technological innovation may be posted in several countries as separate patents, causing double counting. As we ignore this double counting, we assume that an innovation posted as several patents is perceived to be more successful, which in turn is assumed to be an indication for the amount of funds invested in the development of the technology.

Using the previous steps, we end up with a database containing business R&D spending on automotive options. This gives us only half of the story on R&D spending, since in general for every dollar spent by business, there is (roughly) one spent by government. Therefore, we also have to estimate the government expenditure on R&D. As the efforts of the countries leading in automobile industry are concentrated in research programs since the early nineties of the previous century, this is relatively easy.

The result of the database build-up is a number of data sheets with information on car companies (sales, R&D expenditures), patent data and government R&D expenditures. The latter two contain details on the class of vehicles the money is invested in. These classes are Internal Combustion Engine (ICE), Electric Vehicle (EV, also including hybrid vehicles), and Fuel Cell cars (FC). This information is consequently summarized in three sheets, each covering a specific technological option. The information contained in these sheets is the information needed for the SAPIENTIA project, i.e. the sheets are filled according to a pre-defined template. One of these templates is included as an appendix to this document.

9.4. Data on other technologies

As has been shown in the previous section, it is relatively easy to find data on automobiles. At the same time it was noted that the automotive sector provides a rather exceptional showcase, when compared to the situation for other technologies selected in the project, as there it seems less favourable. Nevertheless, in many cases some numbers on public R&D expenditures can be found. In particular, for CCS technologies, an extensive number of projects were undertaken in previous years, and some clear assumptions on the mix of government and private participation can be made. From this, the combined R&D estimate can be estimates, and in turn a decomposition into public and private financing is possible .

For hydrogen technologies, mostly aggregated data on public expenditures is available. Here, we have assumed patent data where available to disaggregate the expenditures over the various technologies. The patents in this case are used both for the estimate of the fraction of the total hydrogen budget, as well as to establish the total cumulative expenditures prior to the statistical information. For the four hydrogen production technologies considered in the project, the assumption on the allocation of the public expenditure r(y) in year y to each of the technologies i can formally be written as

$$r_i(y) = r(y) \cdot \frac{p_i(y)}{\sum_{i=1,4} p_i(y)} \qquad (1)$$

where ri is the budget allocated to technology i and pi(y) are the patents awarded for he technology in the specific year. The estimate for the cumulative expenditures R on a particular technology is based on the same statistics, according to

$$R_i(y) = (1-d) \cdot \sum_{x=y_0}^{y} r_i(x) \cdot \frac{\sum_{x=y_0}^{y} p_i(x)}{\sum_{x<y_0} p_i(x)} \qquad (2)$$

the factor d being a depreciation rate. It is introduced to account for the fact that some of the cumulative knowledge stock will get lost, and should somehow be related to the 'scraping rate' used to depreciate the cumulative R&D investments in the usual framework (Criqui, P. in SAPIENT, 2002). Here, we choose d=0.05, only a little higher than the 'scraping rate' which is 0.03 because we assume that the bulk of the investments are rather recent. We justify this assumption with the observation that the hydrogen technologies show a steep increase in the attention for them.

To determine the contribution from business to R&D expenditures for hydrogen technologies, we assume that this can be approximated by the global, technology-averaged fraction of business-to-public spending, found in the literature (0.63). Since it is unlikely that the average indeed applies to all technologies alike, the impact of this assumption should be subjected to sensitivity analysis. It may be quite determining for the impact of R&D policies, as the fraction directly influences the estimate for the R&D elasticity in the two-factor learning curve (Kouvaritakis, 2005).

References

ACEA, 2004: http://www.acea.be/ACEA/Average_Power-PC-90-02pdf.pdf

ATLAS, 2004: http://europa.eu.int/comm/energy_transport/atlas/html/transport.html

Atzler, F., 2001: On the future of the piston engine with internal combustion. Paper presented at the Marie Curie Fellowship Conference, 19-19 May, 2001, Steyr, Austria.

Bach, B. (2003): The situation in Austria. 1st Workshop EHPA – Education Committee Towards a European Education Scheme. Vienna, 2003.

Beckervordersandforth, C.P. Die Richtung stimmt - Erdgas als Brücke zur idealen Energie, in: Stolten, D.: Brennstoffzellen und Mikro-KWK - Entwicklungen, Akteure, Zukunftsaussichten. International ASUE conference, Dec., 5/6, 2001, Darmstadt. ASUE Schriftenreihe Nr. 20, pp 153-164. Vulkan-Verlag Essen 2001

Bertuleit 2000: Nutzung industrieller Abwärme durch Wärmepumpen mit Kaltwasser-Nahwärme (Kalte Schiene). In IZW-DKV: Wärmepumpen in ge¬werblichen und industriellen Anwendungen. IZW-DKV heat pump status report Nr. 2. IZW/DKV, Hannover/Stuttgart 2000

Beyeler 2004: Lecture at the VSE Kommunikationsforum, August 20th, 2004. www.fws.ch

Blesl (2003): Fuel cells: Bottom-up interpretation of the experience curve. Workshop of EU-EXTOOL and IEA EXCEPT, Paris, January 22-24, 2003.

Blesl et al. 2004: Hochtemperaturbrennstoffzellen und deren Kostenentwicklung. BWK 56 (2004), No. 5, pp72-78

Blesl 2002: Räumlich hochaufgelöste Modellierung leitungsgebundener Energiever sorgungssysteme zur Deckung des Niedertemperaturwärmebedarfs. Ph.D. thesis. IER, University of Stuttgart. Stuttgart 2002

Bock, B., R.Rhudy, H.Herzog, M.Klett, J.Davison, D. De la Torre Ugarte, D.Simbeck, 2003: Economic Evaluation of CO_2 Storage and Sink Options: DOE Research Report DE-FC26-00NT40937 10

David J., Herzog H., The cost of CO_2 capture, MIT, 2003

Department of Energy: Fuel Cell Report to Congress, ESECS EE-1973, February 2003.

Dow teams with GM in 500 unit, 35 MW industrial fuel cell park, world's largest. The hydrogen & fuel cell letter, June 2003.

Duwe, M. (2003): Hydrogen technology overview. Workshop, September 2003.

Edmonds, 2000: REFERENTIE VAN KOEN

EHPA (2003): The French heat pump market development - education of installers. EHPA Education Committee, 3 April 2003.

EWU 1992, 1994, 1999: EWU Engineering GmbH: Kennziffernkatalog Investitions kosten Bereich Wärmeversorgung. EWU. Berlin 1992, 1994, 1999

Faninger, G. Aktueller Markt der Wärmepumpentechnik in Österreich. Working Paper, IFF Klagenfurt, Vienna, Graz, 2004.

Ferreira, C., 1998: Efficiency of Internal Combustion Engines. Economy & Energy, Year II, No 7, Mar/Apr 1998. http://ecen.com/content/eee7/motoref.htm

Fridleifsson, I.B. (1998): Direct use of geothermal energy around the world. GHC Bulletin, December 1998, pp 4-9.

Gaderer 2002: Organic Rankine Cycle (ORC) – Kraft-Wärme-Kopplung bei Verwendung eines organischen Arbeitsmediums in Kombination mit einer Biomassefeuerung. Bayerisches Zentrum für angewandte Energieforschung e.V. (ZAE). Garching 2002

GHT-7 Conference proceedings, 2004

Graus, W.H.J. et al (2003): Inventarisatie warmtepompen 1994-2002. Ecofys, 29 August 2003.

Halozan, H. (2003): Heat pump market developments and strategies in Austria.

Haug et al 1998 : Evaluation and Comparison of Utility´s and Governmental DSM-Programmes for the Promotion of Condensing Boilers. EU-SAVE. IER scientific report, vol. 52, IER, University of Stuttgart. Stuttgart 1998

Heat Pump Test Centre Töss (2003): COP figures published by Heat Pump Test Centre Töss (Switzerland), April 2003.

Hendriks, C., W. Graus, and F. van Bergen, 2002: Global carbon dioxide storage potential and costs. Report Ecofys & The Netherland Institute of Applied Geoscience TNO, Ecofys Report EEP02002, 63 pp.

Herring, S. et al (2003): Development of a high-temperature solid oxide electrolyser system. 2003 hydrogen and fuel cells merit review meeting, Berkeley (US), May 20, 2003.

Herzog H., The economics of CO_2 capture, Greenhouse Gas Control Technologies, Oxford, Elsevier Science Ltd, pp 101-106 (1999)

Hirvonen, J.: Finland - A Rapidly Growing Heat Pump Market. Presentation at the Workshop of the Education Committee (EHPA), Vienna. April, 3rd, 2003

Honda, 2004: http://world.honda.com

http://www.ybiofuels.org/bio_fuels/history_diesel.html

IEA (2003): IEA Heat Pump Programme Annual Report 2002.

Kohlbach 2004: www.kohlbach.at

IEA Heat Pump Centre Newsletter (2002): Volume 20, No. 3/2002.

IEA Heat Pump Centre Newsletter (2003): Volume 21, No. 2/2003.

IEA Heat Pump Centre Newsletter 2004

IEA Heat Pump Centre Newsletter, vol. 21, 1/2003

IEA, 2004: http://www.iea.org/dbtw-wpd/Textbase/stats/defs/rdd.htm#fosfueltp

IEA, 2004: Prospects for CO_2 Capture and Storage

IEA-HEV, 2004: Annex VII - Overview Report 2000 - Worldwide Developments and Activities in the Field of Hybrid Road-vehicle Technology

ITH, 2002: International Herald Tribune/The Asahi Shimbun. 19 November, 2002.

Johns, R.T.(ed.), P.M.Jarrell, C.E.Fox, M.H.Stein, S.L.Webb, 2002: Practical Aspects of CO_2 flooding, Society of Petroleum Engineers Monograph 220 pp.

Joosen, S. et al (2003): Duurzame energie in Nederland 2002. Ecofys en Kema, september 2003.

Kaltschmitt et al. 2003: Erneuerbare Energien. Third edition. Springer Verlag. Berlin 2003

Karlsson, F. et al (2003): Heat pump systems in Sweden – country report for IEA HPP Annex 28. Energy Technology Borås, 2003.

Kaufmann, M. (2003): Electrolytic hydrogen production.

Kleefkens, O. (2004): Personal communication O. Kleefkens, NOVEM (the Netherlands), March 3, 2004.

Leven et al. 2001: Ökonomische und ökologische Bewertung der elektrischen Wärmepumpe im Vergleich zu anderen Heizungssystemen. IER scientific report, vol. 80. Stuttgart 2001

Liu, E. (2003): Large Scale Wind Hydrogen Systems. GE Global Research, September 2003.

Lund, J.W. (2002): Geothermal heat pumps – trends and comparisons, 2002.

Lund, J.W. (2003a): Geothermal heat pumps – an overview. GHC Bulletin, March 2001, pp 1-2.

Lund, J.W. et al (2000a): World-wide direct uses of geothermal energy 2000, Proceedings World Geothermal Congress 2000, Kyushu - Tohoku, Japan, May 28 - June 10, 2000.

Manitoba (2003): Manitoba Energy Development Initiative: Preliminary Hydrogen Opportunities Report, April 2003, p. 37.

Moros R., 1998: Four-stroke cycle Ottocycle. Institut für Technische Chemie, Universität Leipzig, Germany. http://techni.tachemie.uni-leipzig.de/otto/otto_g0_eng.html

Mrowald 1999: Innovationen – Erstes Abwärmekraftwerk nach dem Organic Rankine Cycle-Verfahren in der Zementindustrie. Heidelberg 1999

(www.heidelbergcement.com/html/d/printPage.asp?pageID=268)

mtu 1999: Vorgaben für MCFC-Feedgas, in: Dienhart, H.; Pehnt, M.; Nitsch, J.: Analyse von Einsatzmöglichkeiten und Rahmenbedingungen verschiedener Brennstoffzellen¬systeme in Industrie und zentraler öffentlicher Stromversorgung. DLR. Stuttgart 1999

NeoScan Warmtepompen (2003).

Nilsson, L.J. (2003): Residential Heat Pumps in Germany – Technology, Policy, Actors and Markets.

Obernberger, 2003 Biomass CHP plant based on an ORC process – realised EU demonstration project in Admont/Austria. Presentation at the meeting of the IEA Bioenergy, task 19 “biomass combustion”, Dec. 6-8th, 2000, Broadbeach/Australia

Obernberger, Hammerschmied, 1999: Dezentrale Biomasse – Kraft – Wärme - Kopplungstechnologien. Erneuerbare Energie 1999.

Odyssee, 2004: http://www.odyssee.org

Olivier, C. (2001): Ground-source heat pump in France in the residential sector. EdF Research & Development, 2001.

Pfannstiel 2003 : Keine Besserung in Sicht. Heizung Lüftung/Klima Haustechnik 54 (2003), 6, pp. 8-10

Rawlings, R.H.D. (1999): Ground-source heat pumps - a technology review. Technical Note TN 18/99.

Reijers, H. Th. J. et al (2001): Evaluatie van waterstof-gebaseerde concepten en systemen. ECN-C-01-019.

Rognon, F. (2002): Förderung der erneuerbaren Energien durch das Bundesamt für Energie: Ziele für Wärmepumpen und Umfeld für grosse Wärmepumpen-Anlagen. In: Wärmepumpen: Wo sind die Grossen? 9. Tagung des Forschungsprogramms Umgebungswärme, Wärme-Kraft-Kopplung, Kälte des Bundesamts für Energie (BFE). Bern (Switzerland), 11 June 2002, pp 9-14.

Sanner, B. et al (2001): Examples of ground source heat pumps from Germany.

Shepherd, R., 1999: Trends and Markets in Liquefied gas. The World Bank Group.

Smekens K., Lako P., Seebregts A., Technologies and Technology learning, Contribution to the ETP project, ECN-C-03-046, 2003

The Clean Fuels and Electric Vehicles Report (2003a): The Clean Fuels and Electric Vehicles Report, June 2003, pp 84-86.

The Clean Fuels and Electric Vehicles Report (2003b): The Clean Fuels and Electric Vehicles Report, March 2003, p. 71.

Toyota, 2004: http://www.prius.com

Tsuchiya, Kobayashi, 2002: Fuel Cell Cost Study by Learning Curve. IEW.

Turboden 2004: www.turboden.it

USDOE 2000: Fuel Cell Handbook, 5th edition. United States Department of Energy, Office of Fossil Energy, Morgantown WV. Morgantown 2000

Weindorf, Bünger 1997: Verfahren zur Reinigung von Wasserstoff aus der Erdgasreformierung. BWK 49 (1997), No. 7/8, pp 62-65

Wikapedia, 2004: http://en.wikipedia.org/wiki/Internal_combustion_engine

Wurster, R. et al (1992): Hydrogen energy. In: Energy technologies to reduce CO_2 emissions in Europe: prospects, competition, synergy. Conference Proceedings, Petten, 11-12 April 1994.

Zwaan, B. van der, K. Smekens, 2004: Environmental Externalities of Geological Carbon Sequestration. FEEM working paper 58.2004

INTERNET SOURCES

1. Cropper (2003a): Fuel Cell Market Survey: Large Stationary Applications. Fuel Cell Today, 17 September 2003. Http://www.fuelcelltoday.com
2. Fuel Cell Market Survey: Stationary Applications. Fuel Cell Today, 22 May 2002. Http://www.fuelcelltoday.com
3. PAFC System Survey. Fuel Cell Today, 25 October 2001. Http://www.fuelcelltoday.com
4. Cropper (2003b): Fuel Cell Systems: A survey of worldwide activity. Fuel Cell Today, 5 November 2003. Http://www.fuelcelltoday.com
5. Breakthrough Technologies Institute (2003): Fuel Cells at the Crossroads. Report No. ANL/OF-00405/300. Http://www.fuelcells.org
6. Http://www.crest.org/hydrogen/hydrogen_fuelcell_manufacturers.html#ELECTROLYZERS
7. Worldwide Hydrogen Fuelling Stations. Http://www.fuelcells.org/h2fuellingstations.pdf
8. Rybach, L. et al (2000): Ground-source heat pump systems - the European experience. GHC Bulletin, March 2000, pp 16-26. Http://www.geothermie.de/egec-geothernet/ghc/21-1art4.pdf
9. Http://www.eva.wsr.ac.at/enz/res-dat.htm#h3
10. Hoshino, P.A. (2002): Market transformation of ground-coupled heat pump systems in Canada. Http://www.geothermie.de/egec-geothernet/hoshino.pdf
11. Http://www.nrcan.gc.ca/media/newsreleases/2000/200065_e.htm
12. Http://www.earthenergy.ca/mar00.html
13. Http://www.hptcj.or.jp/about_e/index.html
14. Sanner, B. et al (2003): Current status of ground source heat pumps and underground thermal energy storage in Europe. Http://www.geothermie.de/egec-geothernet/proceedings/szeged/O-4-08.pdf
15. Lund, J.W. et al (2003b): Geothermal (ground-source) heat pumps - a world overview. Renewable Energy World, July-August 2003. Http://www.energieforschung.ch
16. European Heat Pump News (2002a): European Heat Pump News, Issue 3/2, June 2002. Http://www.ehpa.org
17. Http://www.geothermie.de/egec_geothernet/hermes/shallow_resources.htm
18. Http://www.fiz-karlsruhe.de/hpn/html

19. European Heat Pump News (2002b): European Heat Pump News, Issue 4/3, December 2002. Http://www.ehpa.org

20. Http://www.enebc.org/Ingles/enebc/libros/index.htm

21. Http://www.fiz-karlsruhe.de/hpn/html/sales_es.html

22. Rybach, L. et al (2003): The geothermal heat pump boom in Switzerland and its background. International Geothermal Conference, Reykjavík, September 2003. Http://www.fws.ch

23. Zogg, M. (2003): Forschungsvorhaben 2000/2003 des Bundesamts für Energie im Bereich Umgebungswärmenutzung / Wärme-Kraft-Kopplung. Http://www.waermepumpe.ch/fe/Konzept_SIA_99.pdf

24. Http://www.fws.ch

25. Http://www.waermepumpe.ch

26. Lund, J.W. et al (2000b): Geothermal direct-use in the United States update: 1995-1999. Proceedings World Geothermal Congress 2000, Kyushu - Tohoku, Japan, May 28 - June 10, 2000. Http://iga.igg.cnr.it/pdf/0106.pdf

27. Lund, J.W. (2001): Geothermal heat pump utilisation in the United States. Http://geoheat.oit.edu/pdf/tp32.pdf

28. Menzer, M. (1999): Heat pump status and trends in North America. IEA Heat Pump Conference, May 31, 1999. Http://www.ari.org/er/presentations/berlin.pdf

29. Http://www.geoexchange.org

30. Http://www.earthenergy.ca/mar01.html

31. EHPA (2001): The European Heat Pump Association (EHPA) strategy for heat pumps. EHPA Strategy Committee, Final report - 23 March 2001. Http://www.fiz-karlsruhe.de/hpn/html/Strat_report_03_01.pef

APPENDIX A: CO_2 REGIONAL STORAGE CAPACITIES

Table A.1 *Regional storage capacities according to (GHGT-7 proceedinbgs); in the table, depleted fields refer to either oil or gas fields*

	Depleted fields [Gton CO_2]	Depleted fields [Gton CO_2]	ECBM [Gton CO_2]
FSU	177		19
Middle east	197		
USA	47	13-98	35
Canada	17	0.283 (oil) + 2.8 (gas)	12
Western Europe	17	6 (oil) + 30 (gas)	4
Australia			30
China			13
Other Asia			29
Africa			7
Global	455		148

Table A.2 *Regional storage capacities according to (IEA, 2004)*

	depleted fields [Gton CO_2]	EOR/EGR [Gton CO_2]	ECBM [Gton CO_2]	Aquifers [Gton CO_2]
Africa	3-6	3-23	5	1000
Australia	0-1	0-9	50	550
Canada	1-6	6-35	50	1050
China	0-1	0-1	100	550
Eastern Europe	1-2	1-2	20	250
Former Soviet Union	15-30	35-244	100	1000
India	0	0	10	500
Japan	0	0	0	10
Latin America	9-20	20-61	0	1255
Middle East	25-85	20-300	0	505
Other Asia	6-12	11-52	50	1040
USA	10-20	15-30	80	1050
Western Europe	3-5	16-46	30	300
Global	72-187	125-801	495	9060

APPENDIX B: Hydrogen Fuelling Stations

Location	Fuel	Project	In operation since	H_2 production technology	Specifics/
					Comments
Davis, California	Compressed H_2	University of California, Davis	In operation	Air Products delivered LH_2	N/A
Riverside, California	Compressed H_2	University of California, Riverside	1992	PV + Stuart Energy electrolyser	Electrolytic hydrogen generation
El Segundo, California	Compressed H_2	Xerox Corp et al	1995	PV + Stuart Energy electrolyser	Electrolytic hydrogen generation
Thousand Palms, California	Compressed H_2	SunLine Transit Agency et al	Apr-00	Stuart Energy hydrogen fuelling station	Electrolytic hydrogen generation
Sacramento, California	Liquid to compressed H_2	California Fuel Cell Partnership	Nov-00	Air Products and Praxair	LH_2 and compressed H_2
Torrance, California	Compressed H_2	American Honda Motors Co.	Jul-01	N/A	PV-electrolysis + grid backup
Torrance, California	Compressed H_2	Toyota Motor Sales USA	2003	Stuart Energy and Air Products	Electrolysis, 24 kg H_2/day (renewables)
Oxnard, California	Liquid H_2	BMW North America	Jul-01	Air Products delivered LH_2	LH_2 fuelling station
Chula Vista, California	Compressed H_2	City of Chula Vista	2003	Stuart Energy hydrogen fuelling station	60 kg H_2 /day
Thousand Palms, California	Compressed H_2	Schatz Hydrogen Generation Center	1994	PV + Teledyne Energy electrolyser	Electrolysis powered by PV
Richmond, California	Compressed H_2	AC Transit facility	Oct-02	Stuart Energy hydrogen fuelling station	Electrolytic hydrogen generation
San Jose, California	To be determined	VTA, San Mateo Transportation District et al	Target 2004	Air Products delivered LH_2	Current fuelling station will be enhanced
Chicago, Illinois	Liquid to compressed H_2	Chicago Transit Authority et al	March 1998 (February 2000)	Air Products delivered LH_2	N/A
Dearborn, Michigan	LH_2 and liquid to compressed H_2	Ford Vehicle Refuelling Station	1999	Air Products delivered LH_2	N/A
Ann Arbor, Michigan	Liquid to compressed H_2	EPA's NVFEL et al	2003	Air Products	Storage up to 1,500 gallons of LH_2
Arizona (mobile station)	Compressed H_2	Ford Motor Company	2001	Stuart Energy hydrogen fuelling station	Electrolysis (24 kg H_2/day)

Phoenix, California	Compressed H_2	Arizona Public Service	2001	Proton Energy Systems electrolyser	DOE/private sector H_2 station
Northern Nevada	Compressed H_2	Nevada Test Site Development	Nov-02	Air Products	Using 50 kW PEMFC
Washington DC	LH_2 and compressed H_2	General Motors Corp. et al	October 2003 – 2005	Shell Hydrogen	H_2 pump at Shell retail gas station
Penn State, Pennsylvania	Compressed H_2	APCI et al	Fall 2004	N/A	On-site natural gas steam reforming
Munich, Germany	Liquid H_2	Refuelling Station BMW	1989	Linde AG	N/A
Hamburg, Germany	Compressed H_2	W.E.I.T. hydrogen project	1999	Delivered compressed H_2	N/A
Hamburg, Germany	Compressed H_2	CUTE Bus Demo	Target 2003	Hamburgische Electrizitäts-werke AG	Electrolysis powered by renewables
Nabern, Germany	LH_2 and liquid to compressed H_2	Daimler	1998	LH_2 delivered by Linde AG	Linde AG H_2 refuelling technology
		Chrysler Refuelling Station			
Munich, Germany	LH_2 and (liquid to) compressed H_2	Munich Airport Vehicle Project	1999	LH_2 and compressed H_2 delivered by Linde AG	Linde AG H_2 refuelling technology
Wolfsburg, Germany	Liquid H_2	Fuelling of VW hydrogen vehicles	N/A	LH_2 delivered by Linde AG	Linde AG H_2 refuelling technology
Russelsheim, Germany	LH_2 and compressed H_2	Fuelling of GM hydrogen vehicles	N/A	Linde AG supplied LH_2 and compressed H_2	Linde AG technology
Sindelfingen, Germany	LH_2 and compressed H_2	Daimler	Planned	H_2 delivered by Linde AG	Linde AG H_2 refuelling technology
		Chrysler			
Berlin, Germany	LH_2 and compressed H_2	Aral Refuelling Station	Target 2003	H_2 delivered by Linde AG	Linde AG LH_2 refuelling technology
Berlin, Germany	LH_2 and compressed H_2	TotalFinaElf et al	Oct-03	Linde AG supplied LH_2, Proton Energy Systems electrolyser	Linde AG LH_2 refuelling technology
Copenhagen, Denmark	Mobile LH_2	Framework: EU fuel cell bus program	Target 2003	LH_2 delivered by Linde AG	Linde AG mobile LH_2 filling station
Lisbon, Portugal	Mobile LH_2	Framework: EU fuel cell bus program	Target 2003	LH_2 delivered by Airliquido	Linde AG mobile LH_2 filling station
Erlangen, Germany	Mobile LH_2	MAN, Linde AG	December 1996 – 2001	LH_2 delivered by Linde AG	N/A
Oberstdorf Spa, Germany	Compressed H_2	CUTE Bus Demo	Target 2003	BP affiliated	On-site natural gas steam reforming
Stockholm, Sweden	Compressed H_2	CUTE Bus Demo	Target 2003	Stuart Energy hydrogen fuelling station	Central hydro powered electrolysis

London, UK	Compressed H_2	CUTE Bus Demo	Target 2003	BP affiliated	Centralised production via excess H_2 from crude oil
Amsterdam, The Netherlands	Compressed H_2	CUTE Bus Demo	Target 2003	Hydrogen System's IMET® electrolyser	On-site electrolyser
City of Luxembourg	Compressed H_2	CUTE Bus Demo	Target 2003	N/A	On-site methanol steam reforming
Oporto, Portugal	Compressed H_2	CUTE Bus Demo	Target 2003	BP affiliated	Centralised production via excess H_2 from crude oil
Madrid, Spain	Compressed H_2	CUTE Bus Demo	Apr-03	N/A	On-site natural gas steam reforming
Barcelona, Spain	Compressed H_2	CUTE Bus Demo	Target 2003	BP & Stuart Energy, IMET® electrolyser	On-site electrolyser powered by renewables
Reykjavik, Iceland	Compressed H_2	ECTOS Bus Demo	Apr-03	Shell Hydrogen/ Iceland	Geothermal and hydro powered electrolyser
Perth, Australia	Compressed H_2	Daimler Chrysler et al	Target 2004	Centrally produced H_2 at BP refinery	BOC refuelling technology
Victoria, Australia	Compressed H_2	H_2 fuelling station	To be determined	To be determined	Reviewing electrolysis and reforming of natural gas
Beijing, China	To be determined	GEF and UNDP; demonstration of fuel cell buses	Target 2003	N/A	N/A
Shanghai, China	To be determined	GEF and UNDP	Target 2003	N/A	N/A
Cairo, Egypt	To be determined	GEF and UNDP	Target 2003	N/A	N/A
Mexico City, Mexico	To be determined	GEF and UNDP	Target 2003	N/A	N/A
New Delhi, India	To be determined	GEF and UNDP	Target 2003	N/A	N/A
Sao Paulo, Brazil	To be determined	GEF and UNDP	Target 2003	N/A	N/A
Osaka, Japan	Compressed H_2	PEMFC Vehicle Demo	Fall 2001 – end of 2003	N/A	On-site natural gas steam reforming
Takamatsu, Japan	Compressed H_2	PEMFC Vehicle Demo	Fall 2001 – end of 2003	N/A	PEM electrolyser
Tsurumi, Japan	Compressed H_2	PEMFC Vehicle Demo	Aug-02	N/A	N/A
Yokohama, Japan	Compressed H_2	Cosmo Oil JHFC	FY 2002	N/A	Hydrogen and Fuel Cell Demonstration Project
Yokohama, Japan	Compressed H_2	Nippon Oil JHFC	FY 2002	N/A	Hydrogen and Fuel Cell Demonstration Project
Japan	Compressed H_2	Honda Company Filling Stations	2001	N/A	N/A

Japan	Compressed H_2	Toyota Company Filling Station	2001	N/A	N/A
Tokai, Japan	Compressed H_2	Toho Gas Co.	Oct-02	N/A	N/A
Tokyo, Japan	LH_2 and compressed H_2	Iwatani International Corporation et al	Target April 2003 – April 2005	LH_2 from Iwatani and compressed H_2 from Linde AG Cryo-Compressor	Hydrogen and Fuel Cell Demonstration Project
Kawasaki City, Japan	Compressed H_2	Air Liquide Japan JHFC	N/A	Senju	Hydrogen and Fuel Cell Demonstration Project
Vancouver, Canada	CompressedH_2 and H_2/natural gas blend	British Columbia Hydro	2001	Stuart Energy hydrogen fuelling station; electrolyser	Supplies H_2 and H_2/natural gas blend to a variety of vehicles
Montreal, Canada	Compressed H_2	Montreal Urban Transit Authority	1994 (closed in 1994)	Stuart Energy hydrogen fuelling station; electrolyser	N/A
Surrey, Canada	Compressed H_2	BC HydroGen	Fall 2001	N/A	Electrolyser powered by renewables
Torino, Italy	Compressed H_2	PEMFC City Bus Demo	Target 2002/2003	N/A	Hydro powered electrolysis
Bi-cocca, Italy	LH_2 and compressed H_2	Hydrogen and fuel cell demonstration project	2002	AEM, SOL et al	Hydrogen liquefier and vehicle refuelling
Oostmalle, Belgium	Liquid H_2	Belgian Bus Demo	1994	Messer Griesheim GmbH	LH_2 storage
Leuven, Belgium	Compressed H_2	NexBen Fueling	2003	NexBen Fueling	LNG and hydrogen fuelling station
South Korea	Compressed H_2	Hyundai Motor Company	2001	Pressure Products Industries, Inc. (PPI) & Doojin Corporation	PPI two-stage compressor
Singapore	Compressed H_2	Part of BP joint venture	2004	Air Products	20 kg of compressed H_2 per day
Submarine – mobile infrastructure		Class 212 submarine driven by H_2 fuel cells	2002	Air Products (USA)	

APPENDIX C: Specific Description of Data

In Chapter 9, no specific description of the desired data was given. The minimal data set needed to include a technology in the models is given in the upper part of the template in 0D. The main data is denoted as 'Basics' in the table, and appears in the upper part of the appendix. This data is already available for all (relevant) technologies. However, to apply a one-factor learning curve formalism for a technology, also the development of the specific cost of the technology, and it cumulative capacity over the years has to be known.

To be able to apply a 2-factor learning curve approach for a technology, even more data is needed. If available, one should have the cumulative research expenditures, both by government and by business. In many cases, this information will not be available for the technology itself. In such cases, overall spending figures should be provided, plus auxiliary variables from which the share the technology gets from the total can be deduced. Generally, patent data serves as the preferred data for this. A use of patent data as in the case of the automobile is preferred, i.e. the share of expenditures of a technology is proportional to the relative number of patents, implying also the total amount of patents should be known. If the use of data other than patents is proposed, one should give an indication of how to do so.

In the table below the data needed for inclusion of a technology in the models involved in the SAPIENTIA project[3] is given. The table uses a grey-scale coding to indicate which data is needed for which type of description.

---

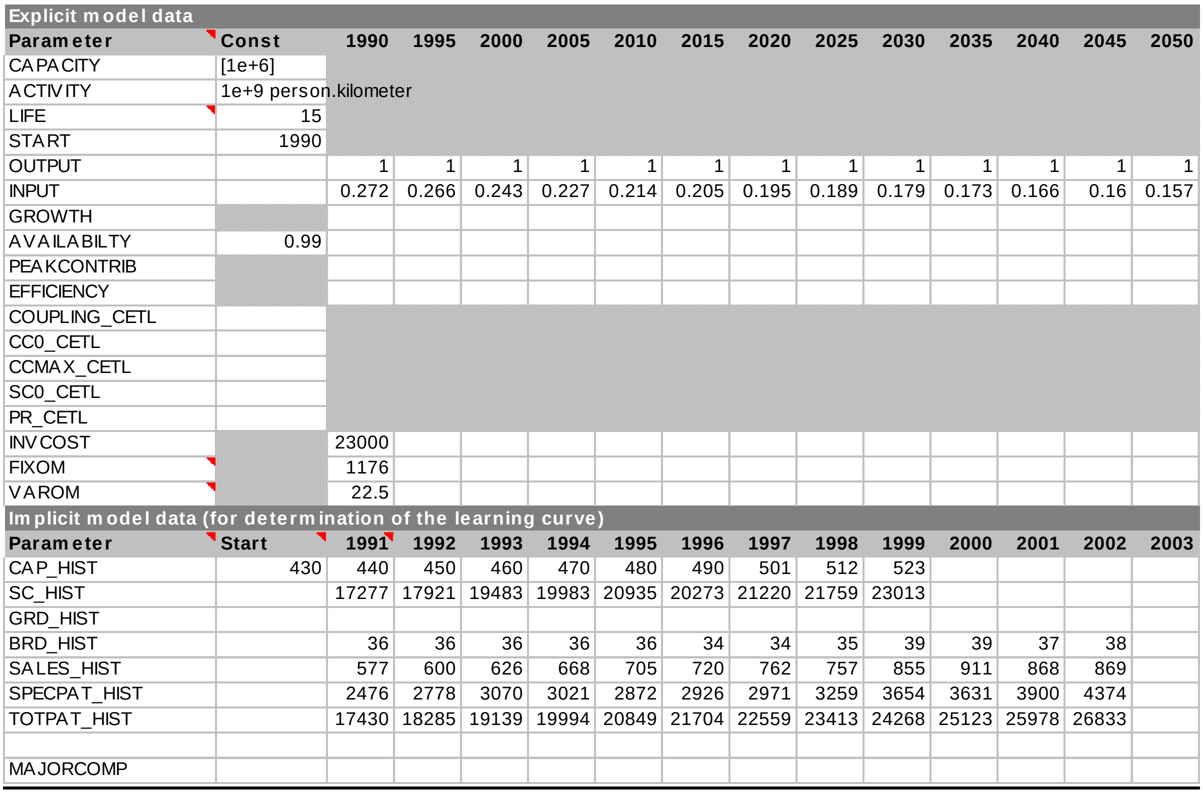
[3] As a matter of fact, it contains only the variables proposed by ECN. The other partners gave no reaction to the proposal, implying but not affirming that the proposal covers all models.

***Table C:* Data requirement for inclusion of a technology in the model(s). Shaded data is required depending on the description used: 1FLC - light grey, 2FLC - middle grey, 2FLC using an auxiliary variable - dark grey**

Parameter	Default Value	Description
Capacity	GW	Unit of capacity
Activity	PJ	Unit of annual activity
Life		Life (economical) in years
Start	1990	First year of availability
Output		Output(s) of the technolgoy, e.g. electricity
Input		Input(s) of the technology, for a conversion technology this includes the fraction needed for one unit of output
Growth	Infinite	Maximum annual growth as decimal fraction, e.g. 1.5 implies a maximal annual growth of 50%
Availability	1	Annual availability, or 1 minus fraction outage resulting repairs, etc.
Efficiency	1	Efficiency of the process. Note: efficiencies for conversion technologies are generally given as numerical value in the specification of the input.
Investment cost		Specific investment cost in million € per unit of capacity
Fixed O&M cost		Costs connected to the annual operation and management in million € per unit of capacity, not depending on actual the output
Variable O&M cost		Costs connected to the annual operation and management in million € per unit of activity, depending on the actual output
Specific costs		Historical evolution of the investment costs in the same time period for which data on the cumulative capacity id known
Cumulative capacity		Historical evolution of the capacity in the same time period for which data on the specific costs are known
Government R&D spending		Historical evolution of the spending by government on R&D into the specific technology under consideration, or on an aggregate containing this technology (in which case an auxiliary variable is also needed)
Business R&D spending		Historical evolution of the spending by business on R&D into the specific technology under consideration, or on an aggregate containing this technology (in which case an auxiliary variable is also needed)
Auxiliary variable	number of patents	(Optional) Historical evolution of the auxiliary variable used for disaggregation of the R&D spending by government and business

As mentioned, the basic data has already been collected by the partners in the project, while only for a few selected technologies specific cost and cumulative capacities are provided, let alone information on R&D expenditures.

APPENDIX D: TEMPLATE CONTAINING THE DESIRED INFORMATION ON TECHNOLOGIES



Explicit model data

Parameter	**Const**	**1990**	**1995**	**2000**	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
CAPACITY	[1e+6]													
ACTIVITY	1e+9 person.kilometer													
LIFE	15													
START	1990													
OUTPUT		1	1	1	1	1	1	1	1	1	1	1	1	1
INPUT		0.272	0.266	0.243	0.227	0.214	0.205	0.195	0.189	0.179	0.173	0.166	0.16	0.157
GROWTH														
AVAILABILTY	0.99													
PEAKCONTRIB														
EFFICIENCY														
COUPLING_CETL														
CC0_CETL														
CCMAX_CETL														
SC0_CETL														
PR_CETL														
INVCOST		23000												
FIXOM		1176												
VAROM		22.5												

Implicit model data (for determination of the learning curve)

Parameter	**Start**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
CAP_HIST	430	440	450	460	470	480	490	501	512	523				
SC_HIST		17277	17921	19483	19983	20935	20273	21220	21759	23013				
GRD_HIST														
BRD_HIST		36	36	36	36	36	34	34	35	39	39	37	38	
SALES_HIST		577	600	626	668	705	720	762	757	855	911	868	869	
SPECPAT_HIST		2476	2778	3070	3021	2872	2926	2971	3259	3654	3631	3900	4374	
TOTPAT_HIST		17430	18285	19139	19994	20849	21704	22559	23413	24268	25123	25978	26833	
MAJORCOMP														

CAP_HIST	Historical development of the total installed capacity
SC_HIST	Historical development of the specific price, i.e. the price per unit capacity
GRD_HIST	Historical governmental expenditures on R&D
BRD_HIST	Historical business expenditures on R&D
SALES_HIST	Historical sales (may either be number or monetary value, specify which)
SPECPAT_HIST	Historical numbers of patents specifically for the technology, applied for by the major companies involved in the development of the technology
TOTPAT_HIST	Historical totals of patents, applied for by the major companies involved in the development of the technology
MAJORCOMP	The major companies involved in the development of the technology

II. TECHNOLOGY DATABASE (TECHPOL)

Philippe Menanteau and Silvana Mima LEPII-EPE
G. Martinus ECN

1. TECHPOL: A Database on the Costs and Performances of new energy technologies

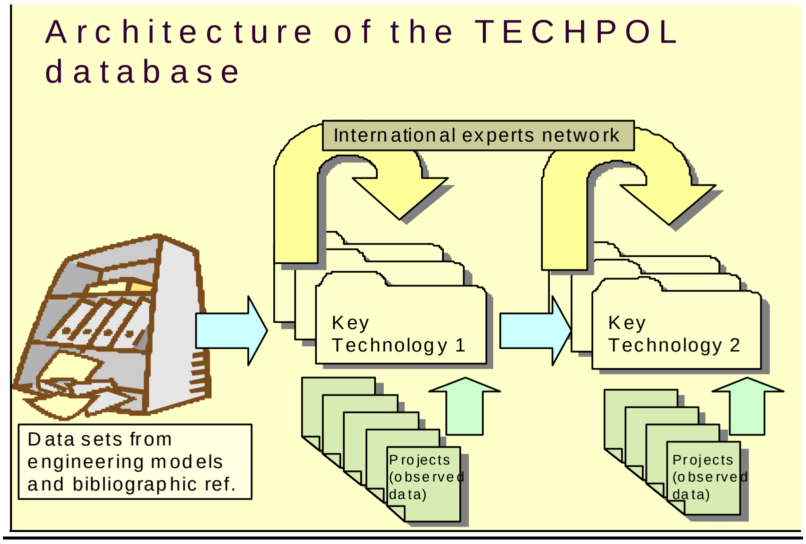
The aim of the TECHPOL database is to provide reliable data on the costs and performances of representative supply and demand energy technologies to be used in large energy sector models.

Because they contain detailed information about energy technologies, these models require a very large number of data sets that should reflect observed performance for existing technologies and, as far as possible, the most accurate assumptions regarding long term performance for emerging and expected technologies. With the development of engineering models in order to integrate disruptive technologies in very low GHG emission scenarios, new requests have appeared for detailed technology information. Particularly, new data on the present and future performance of new energy carriers (hydrogen) and new technologies (capture and storage, 4th generation nuclear, fuel cells, highly energy-efficient technologies) are needed to simulate low carbon emission trajectories.

Information on performance/costs of these new energy technologies may be available but raise different problems of accessibility, comparability and reliability. The TECHPOL database gathers a first set of data on new energy technologies based on reference papers and reports, and expert assumptions. In order to maximise its reliability, the available data has been analysed and processed so as to facilitate the comparability of existing data. Comparing existing data has allowed establishing reference values on costs and performance for key power and hydrogen generation technologies including capture and storage.

The TECHPOL database is built on past experience with technology data collection developed during former European research projects (such as Sapient / Sapientia). Its aim is to go beyond the selective collection of data which may rapidly become out of date when disruptive technologies are concerned. The idea is to collect information on new technologies on a regular basis in order to improve expert judgements regarding future costs and performance and to provide a reliable vision of technical change in the energy sector.

Figure 1-1: Database architecture and data production (Source Techpol)



For this purpose, the database is structured in two separated but inter-related sections. In the first section observed data from past or ongoing specific projects related to new energy technologies is compiled. In the second section, the data do not rely on observation but are intended to reflect the costs and performance of generic technologies (the key technologies). These data are calculated or estimated from the ones gathered in the first section.

As a consequence, the TECHPOL database benefits of a double procedure for the validation of data sets related to key technologies:

- on the one hand, new information coming from ongoing projects and observations is regularly added to the database ; after being organised and processed, these data contribute to the production of reference values ;
- on the other hand, the calculated or estimated data corresponding to generic technologies are compared to the one used in large energy sector models and validated through an interactive process with modelling teams.

With this procedure, the TECHPOL database organises a consolidated interactive process between modellers and technology experts that contributes to improve the quality of the data sets.

In a final step, the TECHPOL database includes a dedicated tool based on an excel sheet which allows to compare the cost of the kWh or hydrogen production using available technologies at different time horizons. This simple analytical tool allows checking the relative costs and performance of different technologies at a given date and their evolution. As such, it improves the cross-consistency of the large number of hypotheses which are further integrated in the modelling process.

1.1. Key technologies for electricity production

In the TECHPOL database, almost 50 different generic technologies are considered, belonging to 4 broad categories.

- centralised / large scale power generation
- distributed or renewable power generation
- hydrogen production
- demand-side / transport technologies

1.1.1. Centralised power generation

Centralised power generation includes both fossil and nuclear electricity production (Table 1-1).

Table 1-1: Key technologies for centralised / large scale power generation

Fossil electricity	Technology	Fuel	CC & Sequ.	Acronyms
	Steam boiler	Fuel	W/O	OCT
	Steam boiler	Natural Gas	W/O	GCT
	Steam boiler	Coal	W/O	CCT
	Steam boiler	Brown Coal	W/O	LCT
	Super Critical Pulverised	Coal	W/O	PFC
	Super Critical Pulverised	Coal	W	PSS
	Gas Turbine	Natural Gas		GGT
	GT Combined Cycle	Natural Gas	W/O	GGC
	GT Combined Cycle	Natural Gas	W	GGS
	Integrated Gasification CC	Coal	W/O	ICG
	Integrated Gasification CC	Coal	W	CGS
	Internal Combustion Engine	Fuel / Gas	W/O	OGC
	Nuclear Power			NUC
	Nuclear Power 4th generation			NND

Source: Techpol

Four different conventional steam boiler power plants have been considered using coal, lignite, natural gas and fuel.

In recent past reference technology for pulverized coal plant used to operate at sub-critical conditions (CCT) but new coal plants which operate at supercritical conditions are progressively entering the market. These new supercritical pulverized coal plants (PFC) have been added to reflect state of the art technology. Integrated gasification plants (ICG) which offer environmental benefits and increased efficiency are considered for the near future.

Gas combustion turbines are divided in two subcategories, simple cycle gas turbines (GGT) which are used mainly for peak electricity production, and combined cycle gas turbines (GGC) which are currently considered as the reference technology for electricity production in many countries.

The changes in the design of nuclear power plants (EPR type reactors) have been taken into account but integrated into the main nuclear power category (NUC). New, intrinsically safe, nuclear power reactors (Fast Breeder Reactors, Gas / Sodium cooled fast reactors, etc.) known as 4th generation reactors are considered in a separate category (NND), in order to reflect the fact that these developments are not expected in the short-medium term.

Finally, internal combustion engines (OGC) for electricity production have also been considered given their contribution to peak production and widespread use in some developing countries.

Three main CO_2 capture technologies have also been introduced for coal and natural gas burning plants. As far as pulverized coal and gas turbines are considered, the capture of CO^2 takes place after combustion (PSS, GGS), while pre-combustion capture is possible with coal integrated gasification combined cycle power plants (CGS)

1.1.2. Distributed or renewable power generation

Key decentralised technologies include both small and large renewable power generation units and fossil distributed production systems (Table 1-2).

Table 1-2: Key technologies for decentralised or renewable power generation

Renewables /	Technology	Fuel	CC & Sequ.	Acronyms
	Large Hydro			HYD
	Micro Hydro			SHY
	Wind Power / on shore			WND
	Wind Power / off shore			WNO
	Concentrating Solar Power			SPP
	Photovoltaics			DPV
	Biomass/Waste combustion			BF2
	Biomass gasification			BGT
	Cogeneration (industrial)			CHP
	Generic Fuel cells	Hydrogen		HFC
	Generic Fuel cells	Natural Gas		GFC

Source: Techpol

Hydro power plants are divided into two broad categories: large hydro (HYD) refers to large-scale power stations, either run-of-river or storage plants and micro hydro (SHY) to small units of less than 10 MW of installed capacity. As far as wind power is concerned, a new category has been introduced, to take into account the separate technical and economic characteristics of off-shore wind power plants.

Two basic solar energy technologies are considered, building integrated PV systems and solar thermal plants. The concentrating solar power category (SPP) is a generic technology as various concentrating technologies can be used for solar thermal plants (parabolic troughs, central receivers and parabolic dishes). The distributed photovoltaic systems category (DPV) covers small distributed power generating units, which may be integrated in new buildings and produce a share of base load electricity demand.

Among biomass power production technologies, two broad categories have been considered: direct combustion or co-firing (BF2) of solid biomass (either wood or waste) and production of electricity via a steam turbine and biomass gasification (BGT) associated with a gas turbine or a combined cycle to produce electricity.

Finally, decentralised cogeneration technologies are described in three distinct categories. Internal combustion engines (CHP) represent current technology for medium to large combined heat and power generation applications in industry. The present variety in fuel cells development has been limited to two different generic technologies using hydrogen directly or natural gas through a reformer. Both of them are supposed to produce heat and power simultaneously.

1.1.3. Hydrogen production

Five different hydrogen production technologies are considered in the TECHPOL database:

Table 1-3: Key technologies for hydrogen production

Hydrogen	Technology	Fuel	CC & Sequ.	Acronyms
	Gas Steam Reforming	Natural Gas	W/O	GSR
	Gas Steam Reforming	Natural Gas	W	GSS
	Coal Partial Oxydation	Coal	W/O	CPO
	Coal Partial Oxydation	Coal	W	CPS
	Biomass Pyrolysis	Biomass	W/O	BPY
	Solar Thermochemical cycle			SHT
	Nuclear Thermochemical cycle			NHT
	Water Electrolysis	Nuclear		WEG
	Water Electrolysis	Electricity		WEN

Source: Techpol

The current technology for hydrogen production, and the most commercially mature, is the gas steam reforming technology (GSR) which can be combined with a capture and storage system (GSS). Coal partial oxidation plants (CPO) are under development; they could also be associated with a capture and storage device (CPS). For medium to long term, hydrogen could be produced via thermochemical cycles using nuclear (NHT) or solar (SHT) at very high temperature. Finally, water electrolysis has also been considered either with dedicated nuclear electricity production or with baseload electricity production from the grid.

1.1.4. Demand side / Transport technologies

This part of the TECHPOL database is still under construction. The objective is to identify appropriate parameters that will allow assessing costs and energy performances for several generic demand-side technologies and energy intensive industrial sector (Table 1-4).

For the time-being, only transport technologies are informed in the database but a first data collection round is engaged for other, building-related, demand-side technologies with the writing of short monographs on each technology.

Table 1-4: Key demand-side technologies / energy intensive sectors

Demand-side				
	Lighting			
	Electric motors			
	Microturbines			
	Batteries (transport)			
	Vehicules 1 (comb. engine)			
	Vehicules 2 (hybrid engine)			
	Vehicules 3 (electric vehicle)			
	Vehicules 4 (Fuel cell)			
	Air conditioning			
	Heat pumps			
	Solar LT 2 (multi family hld)			
	Solar LT 1 (individual hld)			
	Glasses			
	Electric appl. 2 (wet appl.)			
	Electric appl. 1 (cold appl.)			
Industrial sectors				
	Building			
	Iron and steel			
	Cement			
	Paper			
	Alluminium			

Source: Techpol

1.2. Main sources of data

As explained previously, the TECHPOL database is partly based on already existing data. In the core database, several time-series coming from bottom-up energy modelling exercises, have been compiled. Intentionally, a few older sets of data have been maintained, in order to provide a memory of observed progression in performance and of former assumptions regarding technological progress. An illustration of the information sources is given below:

- IPTS, 2000, Technology database for the SAPIENT project;
- Energy Information Administration, 2004, Assumptions for the Annual Energy Outlook;
- International Energy Agency, 2004, Assumptions for the World Energy Outlook;
- ECN, 2003, Contribution to IEA's Energy Technology Perspective;
- CES-KULeuven – VITO, 2001, The Belgian MARKAL database;
- ECN, 1997, CO^2 abatement in Western European power generation;
- DGEMP / DIDEME, 2005, Coûts de référence de la production électrique ;
- SAPIENTIA, 2004, Technology database for the SAPIENT project;
- Royal Academy of Engineering, The cost of generating electricity, 2004;
- Ecofys, 2001, Economic Evaluation of Emission Reduction of Greenhouse Gases in the Energy Supply Sector in the EU Bottom-up Analysis;
- AMPERE, 2000, Commission pour l'Analyse des Modes de Production de l'Électricité et le Redéploiement des Énergies, Sec. d'Etat à l'Energie et au Développement Durable, Bruxelles.

These data have been completed by selective data when complete time-series were not available. For example, long term costs and performance for CO² Capture and Storage technologies have been provided by the following reports:

- VLEEM, 2002, Very Long Term Energy Environment Modelling - Monograph: Options for CO_2 sequestration and enhanced fuel supply
- Anderson & Newell, Resources for the Future, 2003, Prospects for Carbon Capture and Storage Technologies
- David & Herzog, Massachusetts Institute of Technology, 2000, The cost of carbon capture.
- Gielen, International Energy Agency, 2003, The future role of CO² capture and storage.
- National Commission on Energy Policy (USA), 2004, Technical Memorandum – IGCC / CCS recommendations.
- Riahi et al., IIASA, 2004, Long-term Perspectives for Carbon Capture in Power Plants: Scenarios for the 21st Century
- Yamashita & Barreto, IIASA, 2003, Integrated Energy Systems for the 21st Century.

At this stage, a comprehensive coverage of existing literature and available databases was out of reach. The objective was to provide appropriate estimations of costs and performance for new energy technologies, with a focus on CO² Capture and Storage and Hydrogen production technologies, using relevant studies and reports. This first data collection has allowed the integration of almost 135 time-series for present (or past) and future costs of 30 technologies.

In future projects, these estimations will be improved through the enlargement of the data collection process and a systematic validation by a group of technology experts in an interactive process.

1.3. Content of the database

Current data are stored and processed on an Excel sheet but a more user-friendly interface that will facilitate the future assessment and validation process is under development.

The central objective of the TECHPOL database is to collect all data that are necessary for engineering models to analyse and simulate inter-technology competition. As far as electrical power plants are concerned, for example, basic information should allow for the calculation of the discounted production cost for a kWh or a toe of Hydrogen. For this calculation, the following elements are necessary:

- Overnight investment cost
- construction time
- technical lifetime
- load factor
- variable operation & maintenance cost
- fixed O&M cost
- electrical efficiency

As much information as possible is collected in order to keep a detailed description of the technology and a precise characterisation of the data provided. In the database the following information is needed:

- Source of information: who provided this information? Is it a primary or secondary source of information? Who provided the primary data? Have the primary data been observed or estimated? etc.

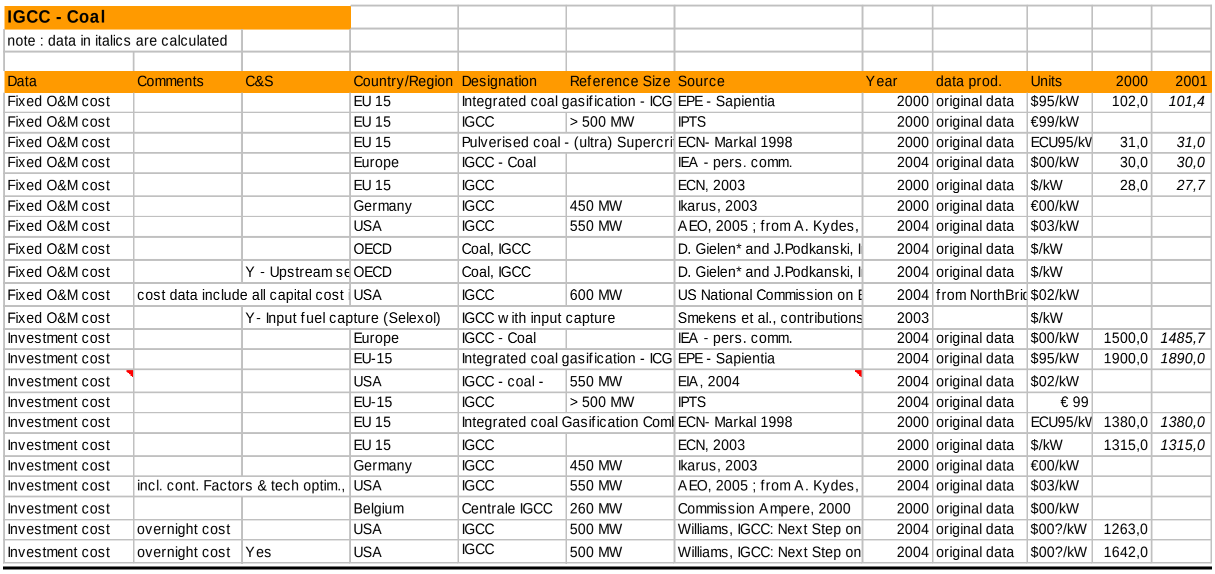
- Date of reference: when have the data been provided / published? What is the date considered for the operation of the plant?

- Type of technology: what precisely is the technology used? What is the average size / capacity? Does the plant include specific equipments (scrubbers for ex.)

- Geographical area: do the data apply to a global technology or is it specific to a region / country (nuclear technology in France for ex.)?

- Nature of data: do the investment costs include interests during construction or are they overnight costs?

Figure 1-2: Illustration of data collected (Access format)



IGCC - Coal

note : data in italics are calculated

Data	Comments	C&S	Country/Region	Designation	Reference Size	Source	Year	data prod.	Units	2000	2001
Fixed O&M cost			EU 15	Integrated coal gasification - ICG		EPE - Sapientia	2000	original data	$95/kW	102,0	*101,4*
Fixed O&M cost			EU 15	IGCC	> 500 MW	IPTS	2000	original data	€99/kW		
Fixed O&M cost			EU 15	Pulverised coal - (ultra) Supercri		ECN- Markal 1998	2000	original data	ECU95/kV	31,0	*31,0*
Fixed O&M cost			Europe	IGCC - Coal		IEA - pers. comm.	2004	original data	$00/kW	30,0	*30,0*
Fixed O&M cost			EU 15	IGCC		ECN, 2003	2000	original data	$/kW	28,0	*27,7*
Fixed O&M cost			Germany	IGCC	450 MW	Ikarus, 2003	2000	original data	€00/kW		
Fixed O&M cost			USA	IGCC	550 MW	AEO, 2005 ; from A. Kydes,	2004	original data	$03/kW		
Fixed O&M cost			OECD	Coal, IGCC		D. Gielen* and J.Podkanski, I	2004	original data	$/kW		
Fixed O&M cost		Y - Upstream se	OECD	Coal, IGCC		D. Gielen* and J.Podkanski, I	2004	original data	$/kW		
Fixed O&M cost	cost data include all capital cost		USA	IGCC	600 MW	US National Commission on E	2004	from NorthBric	$02/kW		
Fixed O&M cost		Y- Input fuel capture (Selexol)		IGCC w ith input capture		Smekens et al., contributions	2003		$/kW		
Investment cost			Europe	IGCC - Coal		IEA - pers. comm.	2004	original data	$00/kW	1500,0	*1485,7*
Investment cost			EU-15	Integrated coal gasification - ICG		EPE - Sapientia	2004	original data	$95/kW	1900,0	*1890,0*
Investment cost			USA	IGCC - coal -	550 MW	EIA, 2004	2004	original data	$02/kW		
Investment cost			EU-15	IGCC	> 500 MW	IPTS	2004	original data	€ 99		
Investment cost			EU 15	Integrated coal Gasification Coml		ECN- Markal 1998	2000	original data	ECU95/kV	1380,0	*1380,0*
Investment cost			EU 15	IGCC		ECN, 2003	2000	original data	$/kW	1315,0	*1315,0*
Investment cost			Germany	IGCC	450 MW	Ikarus, 2003	2000	original data	€00/kW		
Investment cost	incl. cont. Factors & tech optim.,		USA	IGCC	550 MW	AEO, 2005 ; from A. Kydes,	2004	original data	$03/kW		
Investment cost			Belgium	Centrale IGCC	260 MW	Commission Ampere, 2000	2000	original data	$00/kW		
Investment cost	overnight cost		USA	IGCC	500 MW	Williams, IGCC: Next Step on	2004	original data	$00?/kW	1263,0	
Investment cost	overnight cost	Yes	USA	IGCC	500 MW	Williams, IGCC: Next Step on	2004	original data	$00?/kW	1642,0	

Source: Techpol

All the data collected are stored in the original units and then converted through a standard process into euros/dollars, kW, kWh, etc.

2. Costs and Performance of New Energy Technologies: A comparison of Collected Data

In the following chapter, the data collected are analysed in order to provide a first estimation of reference costs and performances for the most important new energy technologies.

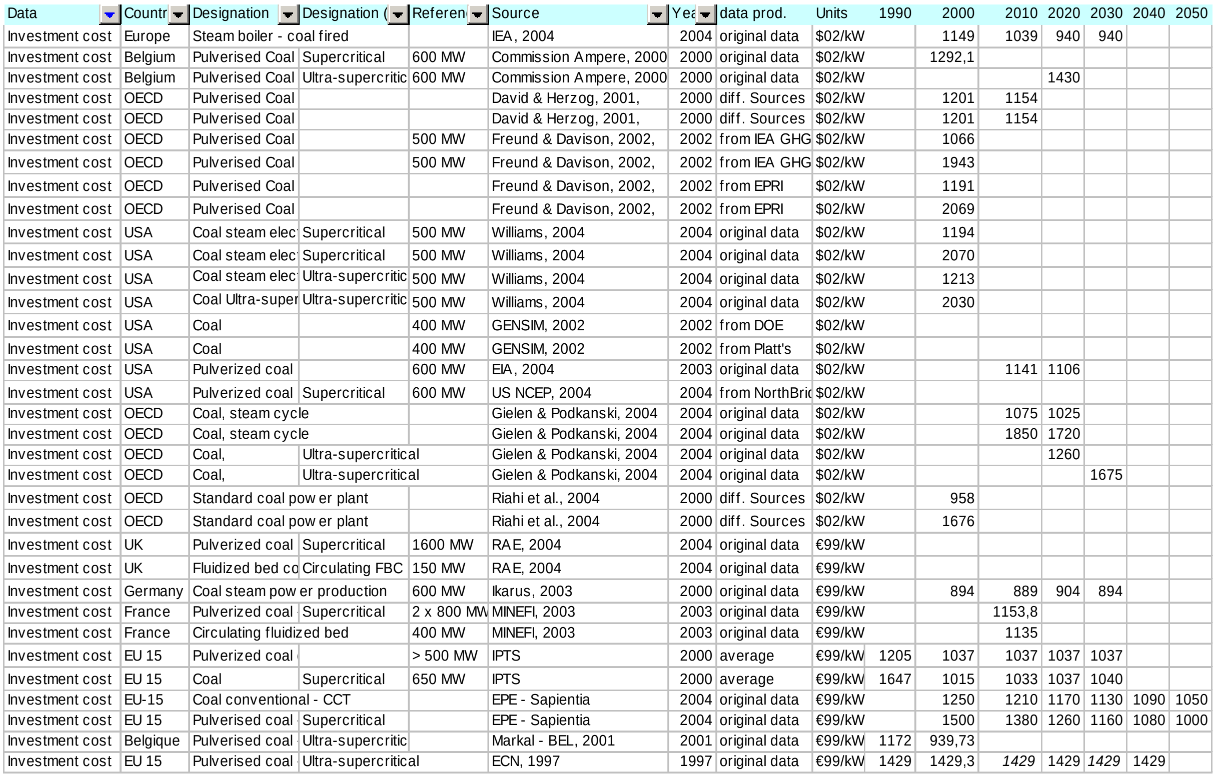
2.1. Centralised electric power plants

This section is mainly focused on fossil fuel power plants. Conventional pulverized coal power plants and integrated gasification in combined cycle are, together with natural gas combined cycle, the key technologies using fossil fuels for centralised base load electricity production. To play a significant part in future supply of electricity they will probably need to equipped with CO^2 Capture and Storage technologies. These developments on fossil fuel power plants are used as an illustration of the possible application of TECHPOL database to estimate reference costs / performances for new energy technologies.

2.1.1. Conventional coal power plants

As far as conventional coal power plants are concerned, 34 different references have been introduced in the database, which provide an initially confused picture for construction cost alone with costs ranging from 895 €/kW to 2070 €/kW in the year 2000.

Figure 2-1: Conventional coal power plants



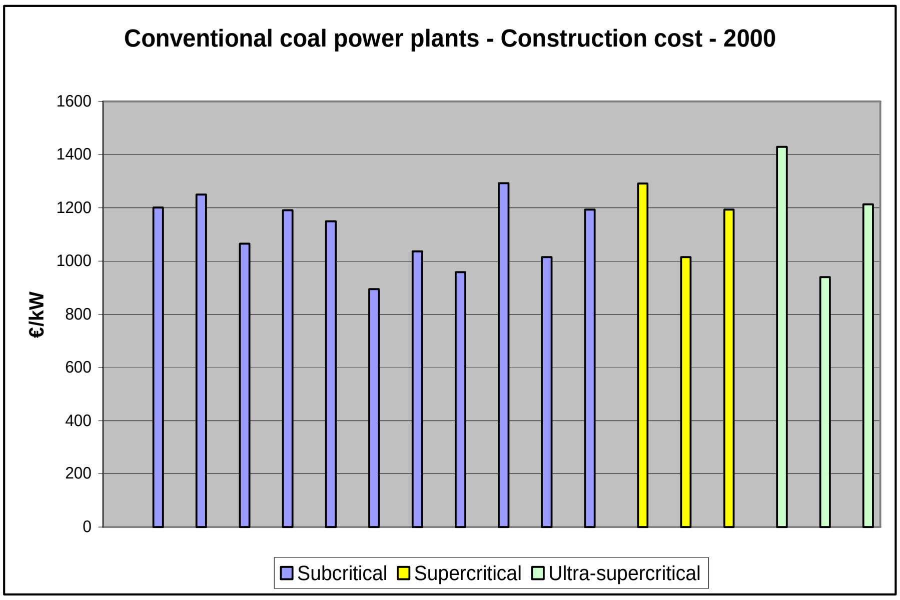
Data	Countr	Designation	Designation (	Referen	Source	Yea	data prod.	Units	1990	2000	2010	2020	2030	2040	2050
Investment cost	Europe	Steam boiler - coal fired			IEA, 2004	2004	original data	$02/kW		1149	1039	940	940		
Investment cost	Belgium	Pulverised Coal	Supercritical	600 MW	Commission Ampere, 2000	2000	original data	$02/kW		1292,1					
Investment cost	Belgium	Pulverised Coal	Ultra-supercritic	600 MW	Commission Ampere, 2000	2000	original data	$02/kW				1430			
Investment cost	OECD	Pulverised Coal			David & Herzog, 2001,	2000	diff. Sources	$02/kW		1201	1154				
Investment cost	OECD	Pulverised Coal			David & Herzog, 2001,	2000	diff. Sources	$02/kW		1201	1154				
Investment cost	OECD	Pulverised Coal		500 MW	Freund & Davison, 2002,	2002	from IEA GHG	$02/kW		1066					
Investment cost	OECD	Pulverised Coal		500 MW	Freund & Davison, 2002,	2002	from IEA GHG	$02/kW		1943					
Investment cost	OECD	Pulverised Coal			Freund & Davison, 2002,	2002	from EPRI	$02/kW		1191					
Investment cost	OECD	Pulverised Coal			Freund & Davison, 2002,	2002	from EPRI	$02/kW		2069					
Investment cost	USA	Coal steam elec	Supercritical	500 MW	Williams, 2004	2004	original data	$02/kW		1194					
Investment cost	USA	Coal steam elec	Supercritical	500 MW	Williams, 2004	2004	original data	$02/kW		2070					
Investment cost	USA	Coal steam elec	Ultra-supercritic	500 MW	Williams, 2004	2004	original data	$02/kW		1213					
Investment cost	USA	Coal Ultra-super	Ultra-supercritic	500 MW	Williams, 2004	2004	original data	$02/kW		2030					
Investment cost	USA	Coal		400 MW	GENSIM, 2002	2002	from DOE	$02/kW							
Investment cost	USA	Coal		400 MW	GENSIM, 2002	2002	from Platt's	$02/kW							
Investment cost	USA	Pulverized coal		600 MW	EIA, 2004	2003	original data	$02/kW			1141	1106			
Investment cost	USA	Pulverized coal	Supercritical	600 MW	US NCEP, 2004	2004	from NorthBric	$02/kW							
Investment cost	OECD	Coal, steam cycle			Gielen & Podkanski, 2004	2004	original data	$02/kW			1075	1025			
Investment cost	OECD	Coal, steam cycle			Gielen & Podkanski, 2004	2004	original data	$02/kW			1850	1720			
Investment cost	OECD	Coal,	Ultra-supercritical		Gielen & Podkanski, 2004	2004	original data	$02/kW				1260			
Investment cost	OECD	Coal,	Ultra-supercritical		Gielen & Podkanski, 2004	2004	original data	$02/kW					1675		
Investment cost	OECD	Standard coal power plant			Riahi et al., 2004	2000	diff. Sources	$02/kW		958					
Investment cost	OECD	Standard coal power plant			Riahi et al., 2004	2000	diff. Sources	$02/kW		1676					
Investment cost	UK	Pulverized coal	Supercritical	1600 MW	RAE, 2004	2004	original data	€99/kW							
Investment cost	UK	Fluidized bed co	Circulating FBC	150 MW	RAE, 2004	2004	original data	€99/kW							
Investment cost	Germany	Coal steam power production		600 MW	Ikarus, 2003	2000	original data	€99/kW		894	889	904	894		
Investment cost	France	Pulverized coal	Supercritical	2 x 800 MW	MINEFI, 2003	2003	original data	€99/kW			1153,8				
Investment cost	France	Circulating fluidized bed		400 MW	MINEFI, 2003	2003	original data	€99/kW			1135				
Investment cost	EU 15	Pulverized coal		> 500 MW	IPTS	2000	average	€99/kW	1205	1037	1037	1037	1037		
Investment cost	EU 15	Coal	Supercritical	650 MW	IPTS	2000	average	€99/kW	1647	1015	1033	1037	1040		
Investment cost	EU-15	Coal conventional - CCT			EPE - Sapientia	2004	original data	€99/kW		1250	1210	1170	1130	1090	1050
Investment cost	EU 15	Pulverised coal	Supercritical		EPE - Sapientia	2004	original data	€99/kW		1500	1380	1260	1160	1080	1000
Investment cost	Belgique	Pulverised coal	Ultra-supercritic		Markal - BEL, 2001	2001	original data	€99/kW	1172	939,73					
Investment cost	EU 15	Pulverised coal	Ultra-supercritical		ECN, 1997	1997	original data	€99/kW	1429	1429,3	*1429*	1429	*1429*	1429	

Source: Techpol

The differences are narrowing when power plants with CO^2 Capture and Storage are excluded, and power plants discriminated according to their operating mode (subcritical versus supercritical). The results are presented in the following figures.

In 2000, the average value of construction (overnight) cost for conventional coal power plants (pulverized coal) is 1113 €/kW for subcritical conditions, 1167 €/kW for supercritical conditions and 1194 €/kW for ultra-supercritical conditions. The dispersion is large for ultra-supercritical plants but most figures are in the range of 1000 - 1200 €/kW for coal fired power plants operating in sub or supercritical conditions (Figure 2-2)

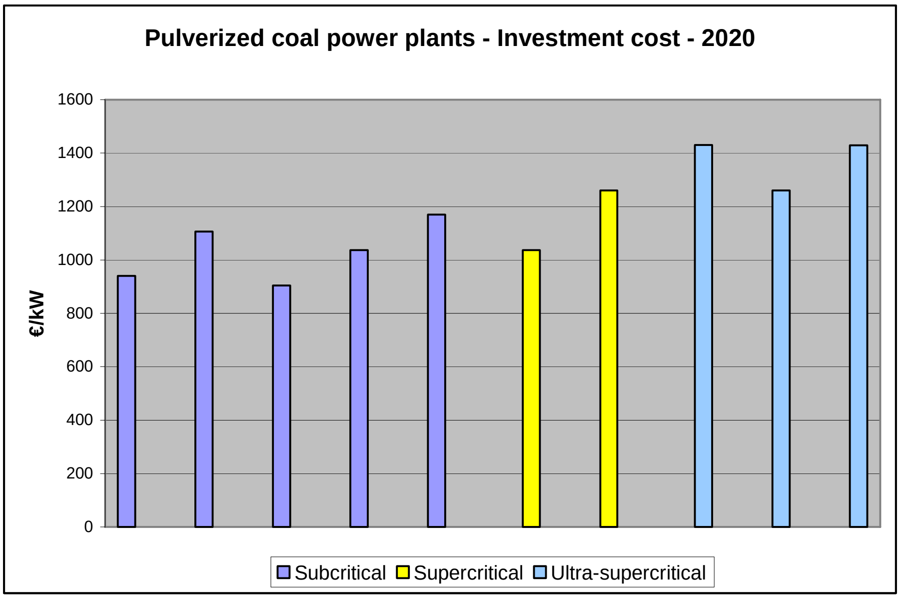
Figure 2-2: Coal power plants – Construction cost in 2000



Source: Techpol

Expected technological progress on coal fired power plants is limited at least for conventional plants. Construction costs are only slightly lower for plans operating in sub and supercritical conditions (1030 €/kW and 1148 €/kW respectively). The uncertainty associated to the date of penetration on the market of ultra-supercritical technology may explain that some estimates for 2020 are higher than other for 2000 (1373 €/kW versus 1194 €/kW). The gap is nevertheless narrowed in 2020 reflecting more converging estimates (Figure 2-3).

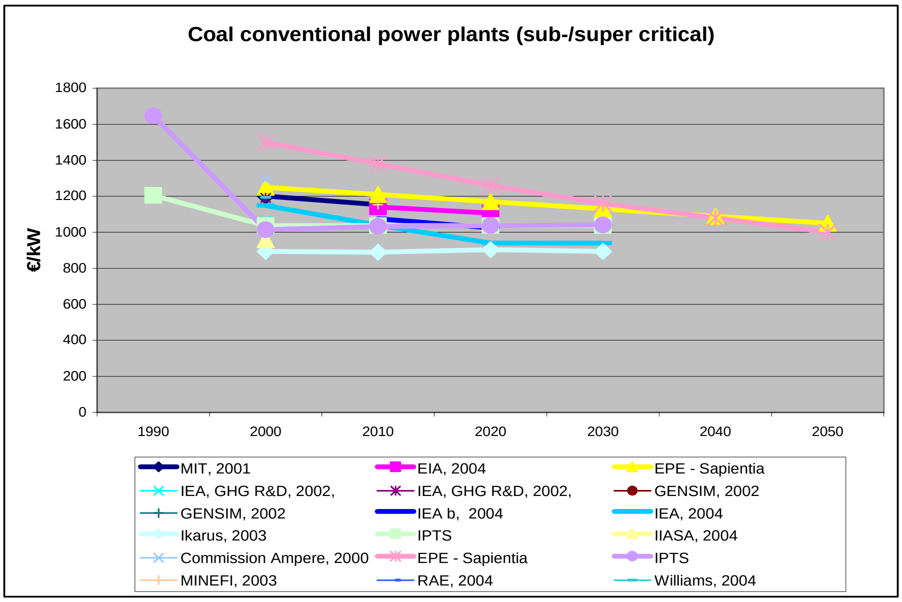
Figure 2-3: Coal power plants – Investment cost in 2020



Source: Techpol

Finally, the reference construction cost for conventional coal power plants stands between 1000 – 1200 €/kW for sub or supercritical conditions with only a slight decrease in costs expected in the next decades (Figure 2-4).

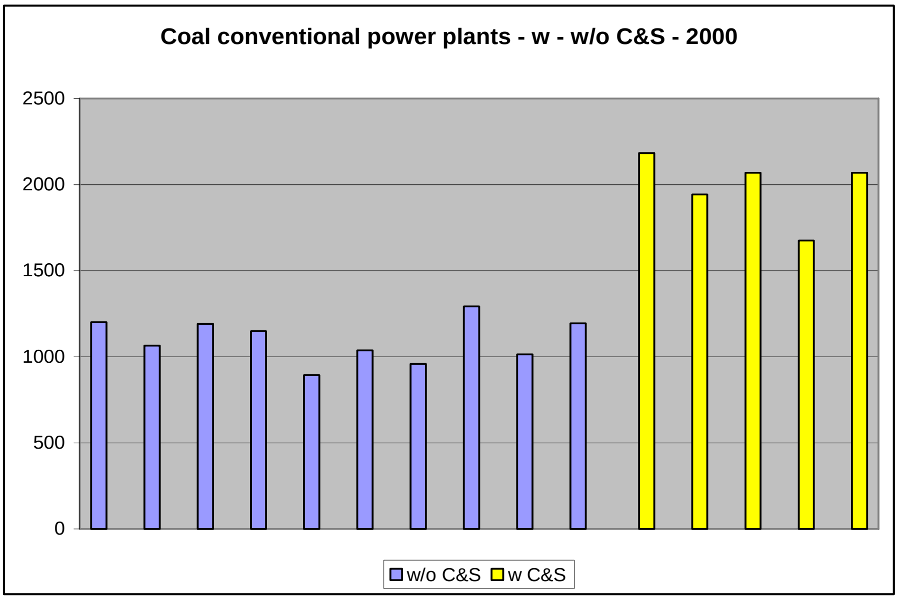
Figure 2-4: Conventional coal plants - expected technological progress (for construction cost)



Source: Techpol

The introduction of carbon capture and storage technology strongly increases the construction cost of conventional coal power plants (Figure 2-5). Construction costs of coal power plants with CO_2 Capture and Storage stands between 1700 and 2200 $/kW. The average incremental cost for CCS device is 890 €/kW (i.e. 80 % of the cost of the reference plant).

Figure 2-5: Conventional coal power plants with CCS

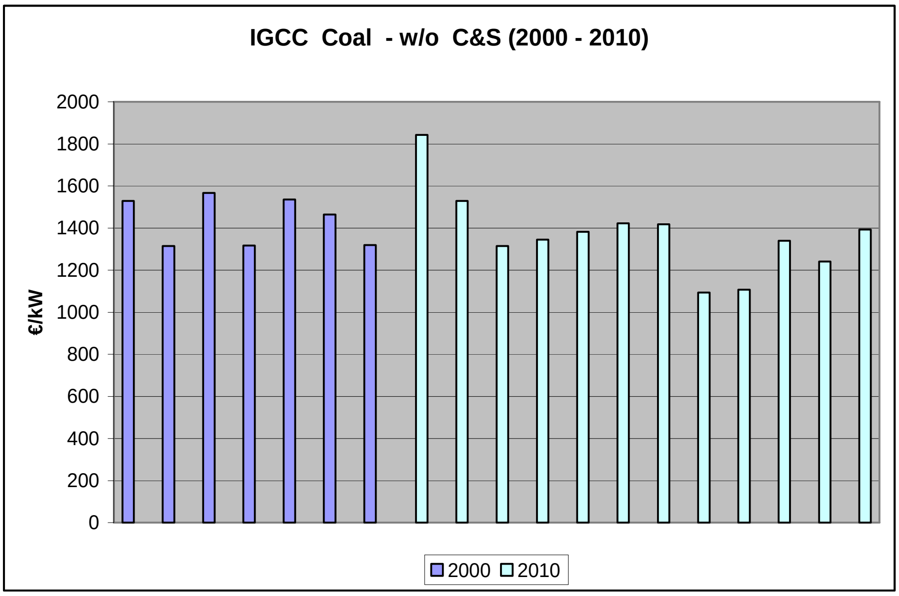


Source: Techpol

2.1.2. Integrated coal gasification with combined cycle (IGCC)

Most references used in the database expect IGCC to reach the market in 2010. The dispersion in 2010 is mainly due to older references which may be considered as less relevant today (Figure 2-6). These references being excluded, the construction cost of IGCC is estimated between 1300 – 1600 €/kW in 2000 and 1050 – 1450 €/kW in 2010. Average values are respectively 1500 €/kW and 1350 €/kW

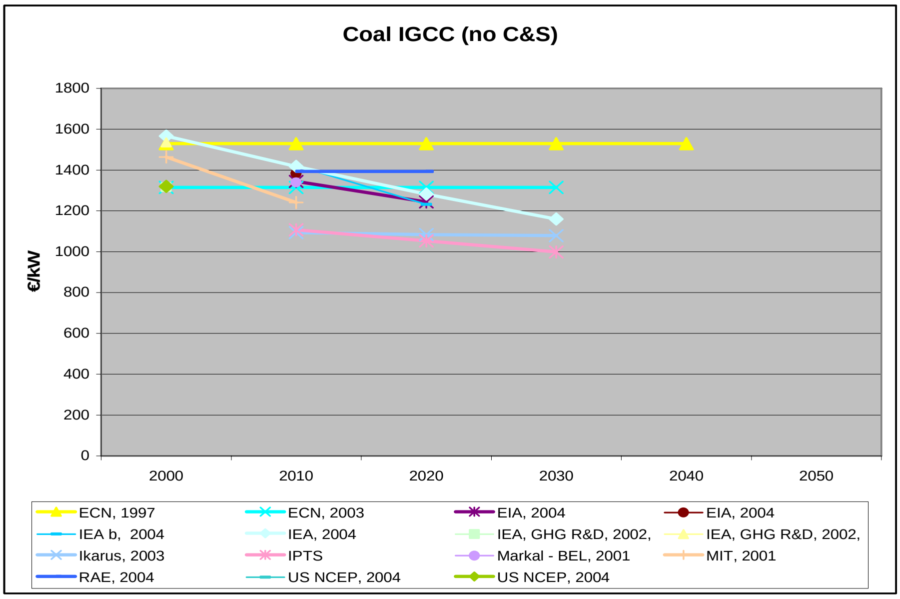
Figure 2-6: Coal Integrated Gasification Combined Cycle



Source: Techpol

According to the most recent estimates, the construction cost of IGCC should decrease more sharply than conventional coal construction costs on the period 2010-50 from 1300 - 1500 €/kW in 2010 to 1000 - 1200 €/kW in 2050 (Figure 2-7).

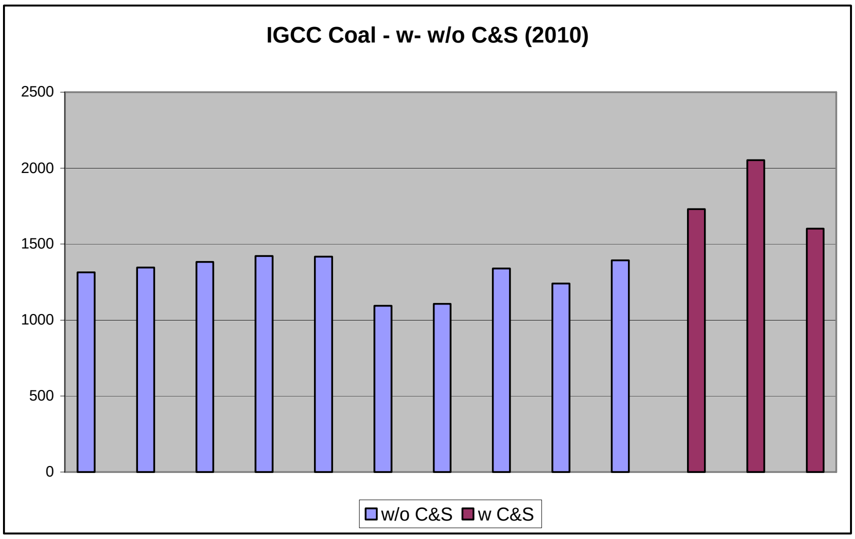
Figure 2-7: IGCC - Expected technological progress (construction cost)



Source: Techpol

The introduction of CCS raises the cost but not as much as for conventional plants because of less expensive upstream capture technology (Figure 2-8). The construction cost of IGCC with CCS device stands between 1600 - 2000 €/kW, the average incremental cost being 450 €/kW.

Figure 2-8: Coal IGCC with CCS



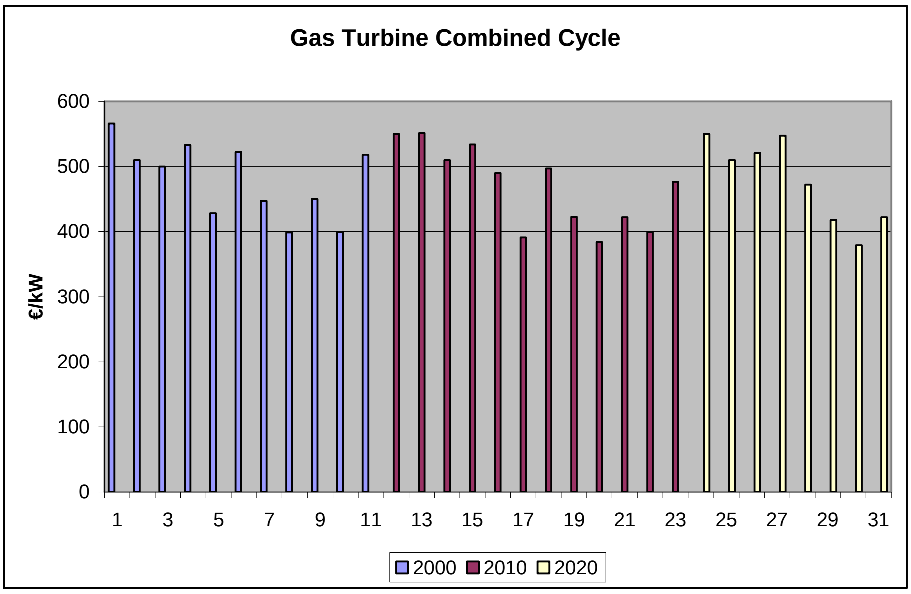
Source: Techpol

2.1.3. Gas Turbine combined cycle

In a large number of countries, gas turbine combined cycles are the reference technology for baseload electricity production. In spite of a large diffusion, the dispersion in construction costs is still quite large. Curiously, most recent estimates do not systematically provide the lower figures; on the contrary a slight increase in construction costs is apparent in the sources from 2002-2004.

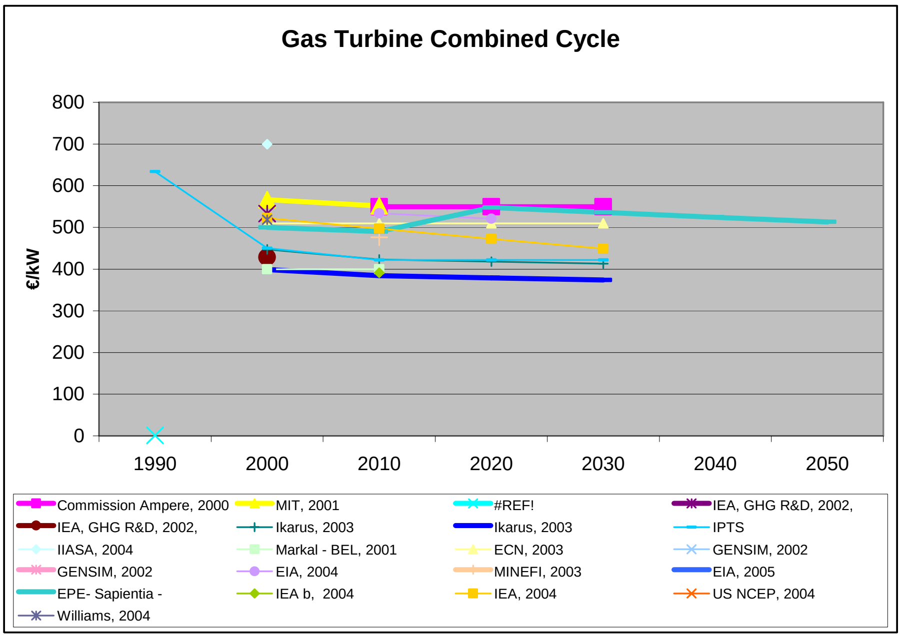
The GTCC has reached technical maturity and foreseen technological progress is very limited according to the cost expectations for 2010 – 2020 (Fig 12). The reference cost for GTCC is situated between 400 and 500 €/kW in 2000 and it does not decrease in the next two decades: according to the data collected in the database, the cost is on average, 480kW, 470 €/kW and 480 €/kW respectively in 2000, 2010 and 2020. The picture is not significantly different when the time horizon is extended to 2030 or 2040 (Fig 2-9).

Figure 2-9: Gas Turbine Combined Cycle



Source: Techpol

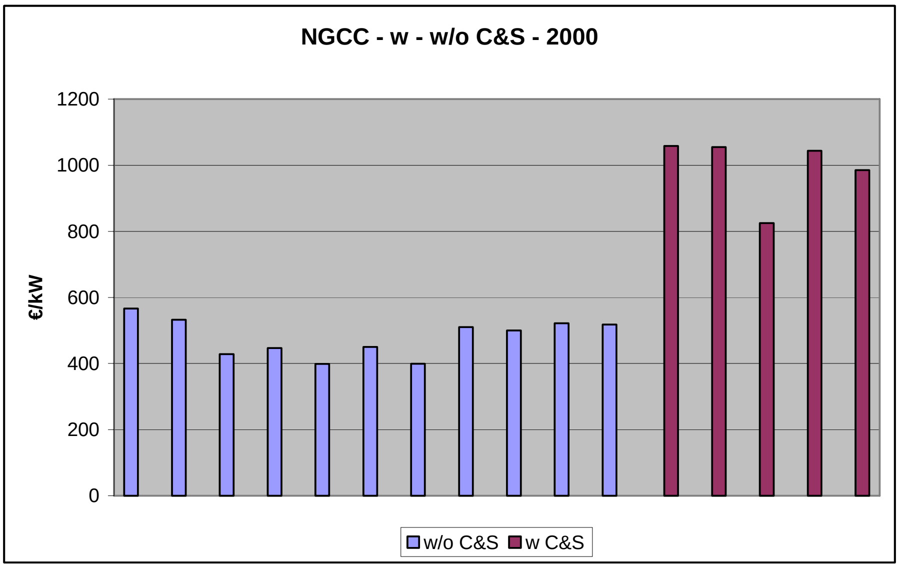
Figure 2-10: GTCC - Expected technological progress



Source: Techpol

Introduction of CCS device significantly raises the construction cost of GTCC because of the lower carbon content of natural gas. The average cost is more than doubling with an increase from 480 €/kW to almost 1000 €/kW.

Figure 2-11: Gas Turbine Combined Cycle with CCS



Source: Techpol

The most important cost and performance parameters for fossil fuel power plants with and without CO_2 Capture and Storage are presented in Table 2-1

Table 2-1: Main cost and performance parameters for coal / gas power plants

			2000	2020				2000	2020
CCGT w/oC&S	Investment	€99/kW	480,00	475,00	CCGT w C&S	Investment	€99/kW	1 000,00	780,00
	VOM	€99/MWh	1,75	1,70		VOM	€99/MWh	5,00	nd
	FOM	€99/kW	18,00	16,00		FOM	€99/kW	10-75	30
	Efficiency	%	55,00	60,00		Efficiency	%	45,00	51,00
			2000	2020				2000	2020
PC w/o C&S	Investment	€99/kW	1145	1145	CCGT w C&S	Investment	€99/kW	2000	1720
	VOM	€99/MWh	2,50	2,50		VOM	€99/MWh	20,00	10,00
	FOM	€99/kW	25-40	25-40		FOM	€99/kW	nd	45
	Efficiency	%	42,00	46,00		Efficiency	%	31,00	36,00
			2000	2020				2000	2020
IGCC w/o C&S	Investment	€99/kW	1500	1350	CCGT w C&S	Investment	€99/kW	1 930,00	1 600,00
	VOM	€99/MWh	5	3		VOM	€99/MWh	12,00	nd
	FOM	€99/kW	50,00	47,00		FOM	€99/kW	nd	50
	Efficiency	%	45,00	50,00		Efficiency	%	37,50	40,00

Source: Techpol

2.2. Decentralised electric power plants

The following section is focused on the main decentralised power plants using renewable energy sources: photovoltaic power plants, concentrating solar power plants, off- and on-shore wind power plants and biomass power plants.

2.2.1. Photovoltaics

The available data on photovoltaic power systems costs presents a rather heterogeneous picture with a limited dispersion in 2000 and increasing gaps between lower and higher values in 2010 and 2020 (Figure 2-12).

On the whole, investment cost decreases sharply from 2000 to 2020 (respectively 6200 €/kW, 4200 €/kW and 3300 €/kW) but the dispersion increases due to different assumptions regarding technological progress. If the higher figures are removed (coming from the same source), the assumptions focuses on a range of costs between 2000 - 3000 €/kW in 2020 and 1250 - 2500 €/kW in 2030 (Figure 2-13).

Figures for PV load factors logically present great differences as they vary according to the location (average load factor for USA is almost the double of average value for Europe; 26 % and 13 % respectively). The huge dispersion of figures for fixed O&M costs may be explained by the inclusion of variable O&M for some sources. The gap remains nevertheless important between lower and higher values when all figures are expressed in €/kWyr reflecting differences in system sizes and probably uncertainty regarding real operation and maintenance costs of operating systems. As a consequence it does not appear possible on the basis of available data to propose reference O&M reference costs for PV technology.

__Figure 2-12: Photovoltaic power plants - Investment costs__

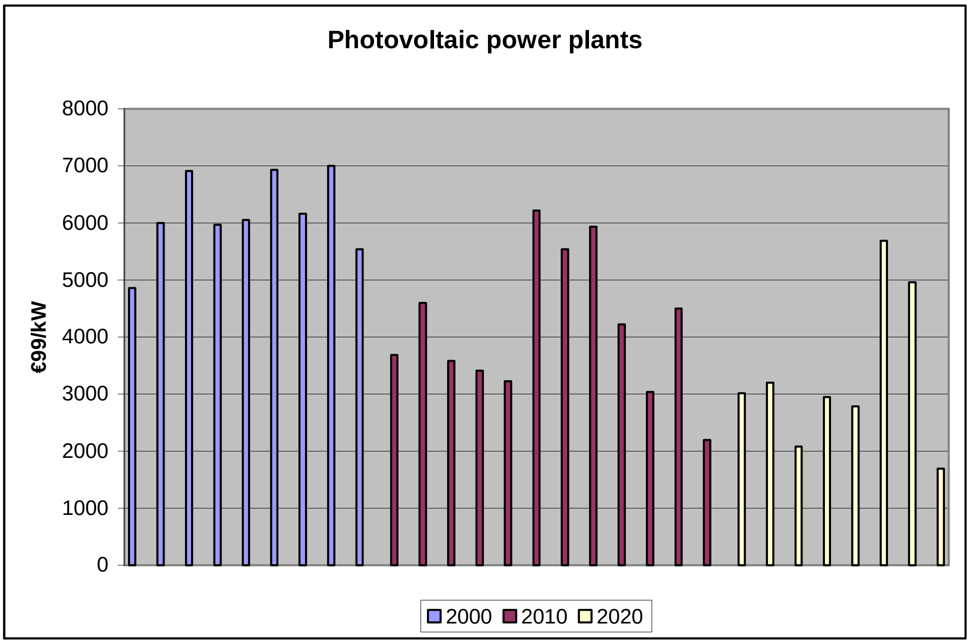
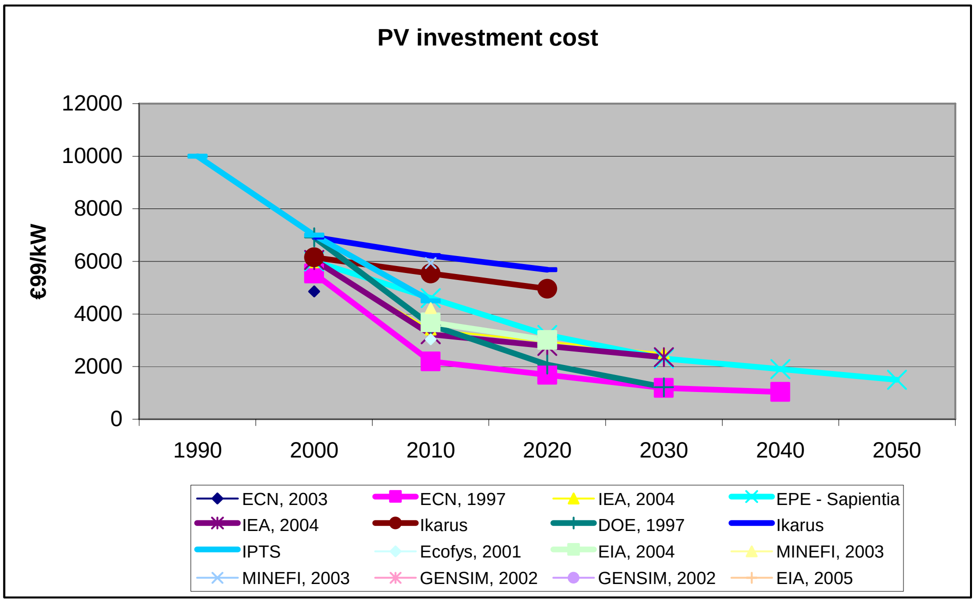


__Figure 2-13: PV - Expected technological progress__



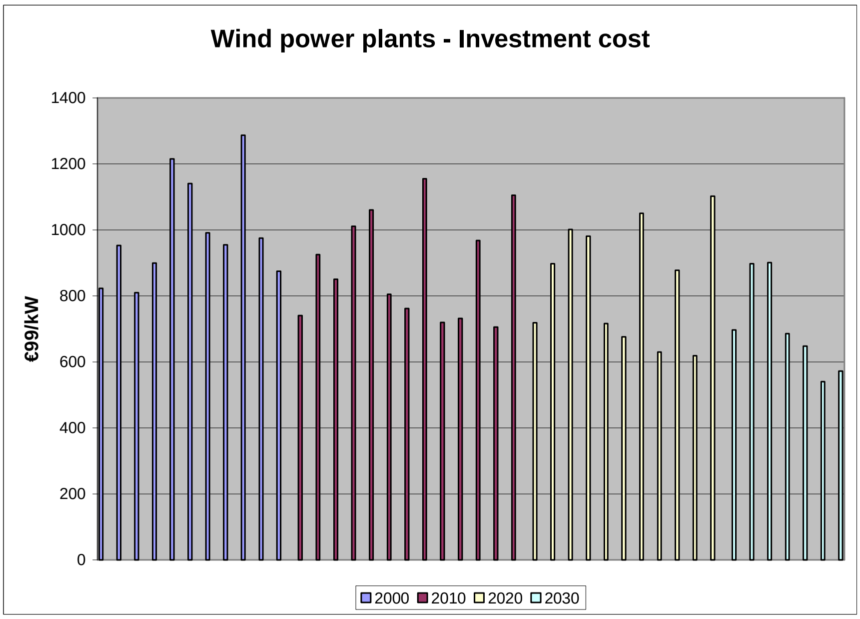
__Source: Techpol__

2.2.2. Wind power plants

Available data for wind power plants present two main characteristics:

- still a large dispersion in the estimates of investment costs in spite of the important cumulated installed capacity – surprisingly, the higher estimates are provided by convergent assumption (2004 and 2005) from the EIA for the USA
- and a limited expected technological progress on the next decades.

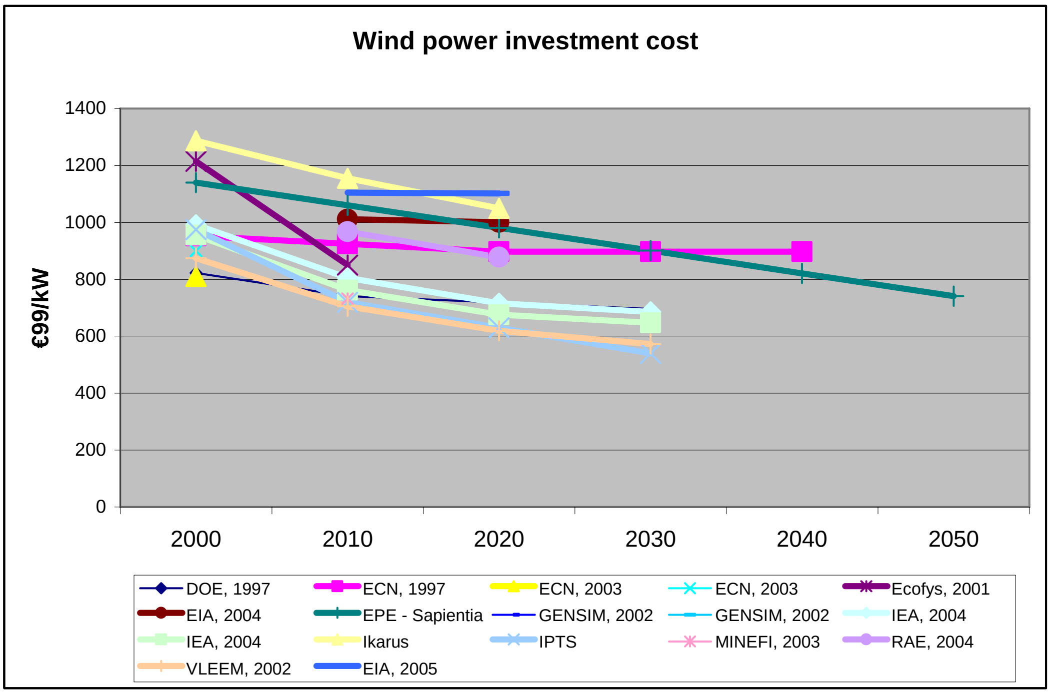
Figure 2-14: Wind power plants (on –shore)



Source: Techpol

The higher assumptions, which refer to the North American situation may be related to the specific US experience with wind energy. These being excluded, the expected trend for technological progress is rather consistent from one source to another. The average investment cost for on-shore wind power plant progressively decreases from 1000 €99/kW in 2000 to 890 and 840 in 2010 and 2020 respectively. The floor cost is situated between 600 – 700 €/kW.

Figure 2-15: Wind power plants - Expected technological progress

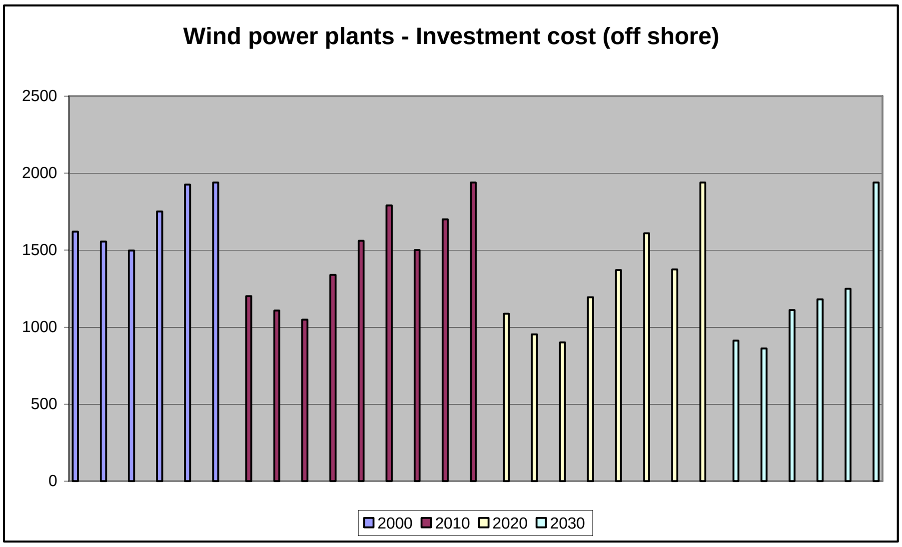


Source: Techpol

As in the case of PV systems, load factors depend on the location of wind farms, i.e. of the quality of the wind resource, and as a consequence may vary from one source to another. Load factor is estimated between 25 and 30 % (2200 and 2600 hours) with an average value of 27% in 2000 slightly increasing to 32 % in 2020. Data on variable O&M are limited but most estimates are lie between 3 and 10 €99/MWh. Data on fixed O&M are more numerous and mostly situated between 15 and 25 €/kW.yr (1.5 – 2.0 % of investment) with an average value of 20 €/kW decreasing to 15 €/kW in 2020.

As far as off-shore wind is concerned, dispersion is logically higher than for on-shore wind: technology is not yet mature and operating experience is still limited. As a consequence, assumptions regarding present and future costs differ from one source to another and even if most assumptions seem to converge towards a range of 900 to 1100 €/kW in 2030, the dispersion on cost is still large at that time. Under these conditions, a reference cost is difficult to estimate : for information, the average investment cost goes from 1715 €99/kW in 2000 to 1300 €99/kW in 2020 and 1200 €/kW in 2030. Similarly, available data are not sufficient in order to estimate a reference value (between 25 and 35%). Fixed O&M are mostly situated in the margin 35 – 45 €99/kW.yr

Figure 2-16: Wind power plants (off –shore)

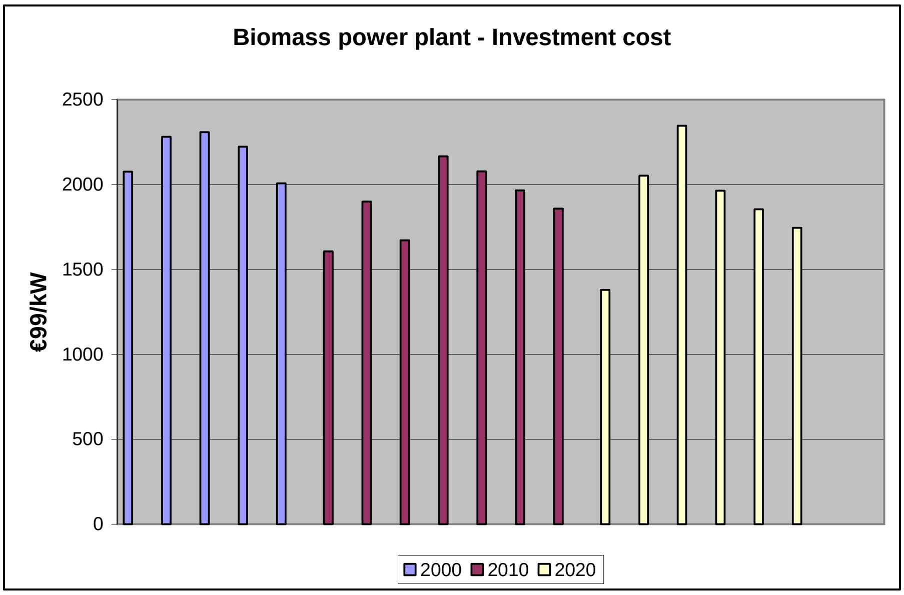


Source: Techpol

2.2.3. Biomass power plants (gasification)

As in the case of PV and wind power plants, biomass power could be a major contributor to future electricity supply from renewable sources. Integrated gasification associated with a combined cycle is the most promising technology for cost-effective electricity production from biomass but industrial experience is still limited to pilot plants. Technical immaturity is reflected in the dispersion of investment costs and a low expected rate of technological progress (Figure 2-17): costs in 2020 are not significantly lower than costs in 2000, reflecting some degree of uncertainty regarding the period of industrial development.

Figure 2-17: Biomass power plants



Source: Techpol

Investment cost varies from 2000 - 2300 €99/kW in 2000 to 1400 - 2350 €99/kW in 2020 with average values respectively of 2180 €99/kW and 1850 €99/kW. Fixed O&M costs for biomass integrated gasification power plants are close to FOM for conventional coal power plants in a range from 25 to 50 €99/kW with an average value of 43 €99/kW decreasing to 38 €99/kW in 2020. Variable O&M cost is clearly lower for biomass power plants with an average value of 3.1 €99/MWh in 2000 (from 2.5 to 5.0 €99/MWh).

2.3. Hydrogen production technologies

The data collected on hydrogen production technologies are still insufficient to allow a comparison of multiple information sources of cost and performance figures as in the case of fossil fuel or renewable power plants. These data will be presented in the following section within a harmonized framework for the comparison of electricity and hydrogen production costs, together with road passenger transport costs.

3. An Harmonised Framework for the Comparison of Production Costs

In order to reinforce the quality of the data collected a complementary tool has been developed in the TECHPOL database. Its aim is to facilitate the comparison of production (for electricity and hydrogen) and transport costs (for road passenger) within a harmonised framework. This framework provides a standardized calculation procedure for electricity / hydrogen levelised production costs. It allows visualising the combined effects of different factors that may influence production cost and facilitates a more accurate assumption of the future evolution of key parameters (such as investment cost, efficiency, variable or fixed O&M). In the following sections, the results for electricity and hydrogen production, and road passenger transport are presented.

3.1. Electricity production costs

Electricity production costs are calculated using a conventional total discounted cost approach. This calculation is performed in a multi-stage process.

3.1.1. The discounted cost calculation process

Total investment (INV): overnight cost (OIC) plus other costs (OCS), decommissioning (DSH) and interest during construction:

$$INV = OIC*(1+DSH*EXP(-DRT*LFT)) / (((1+IRT)CNT-1)/(IRT*(1+IRT)CNT))*CNT+OCS$$

with,

OIC : overnight cost
OCS : other costs
DSH : decommissioning share
DRT : discount rate
LFT : lifetime
IRT : interest rate
CNT : construction time

Fixed annual cost (FAC): annualised cost corresponding to the total investment cost

$$FAC = INV/(((1+DRT)LFT-1)/(DRT *(1+ DRT)LFT))$$

Fixed cost (FCT): fixed annual cost plus fixed operation and maintenance costs, per kWh

$$FCT = (FAC+FOM)/8760*1000/LDF$$

with,

FOM : fixed operation and maintenance cost

LDF : load factor

Variable cost (VCT): variable cost per kWh including fuel cost and carbon tax

$$VCT = (FPC+(CCT*CTX))*0,086/EFF+ VOM$$

with,

FPC : fuel price
CCT : carbon content
CTX : carbon tax
EFF : fuel efficiency
VOM : variable operation and maintenance cost

Production cost: discounted kWh production cost

$$PCT = FCT + VCT$$

For those electricity production technologies which may integrate carbon capture, the calculation of the variable cost is slightly different taking into account capture efficiency

Variable cost with carbon capture

$$VCT=(FPC +CCT*(1-CEF))*CTX)*0.086/EFFCC + VOMCC$$

with,

EFF_{CC}: fuel efficiency taking account of carbon capture

VOM_{CC}: variable operation and maintenance cost taking account of carbon capture

CEF: efficiency of carbon capture

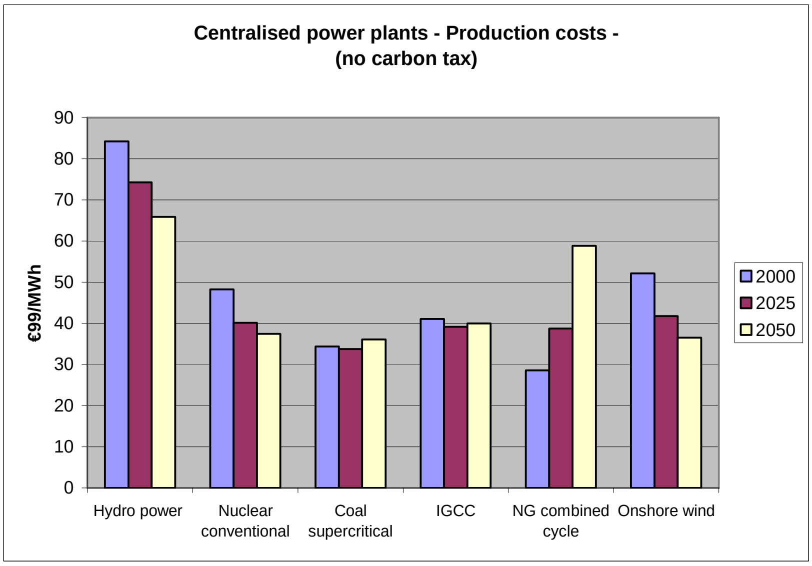
3.1.2. KWh Cost comparison – Centralised power plants

An illustration of production costs for centralised power plants (without carbon capture) is given below. The results refer to reference values from the database for generic technologies and energy prices scenario for the USA (according to the POLES model) without carbon tax in Figure 3-1, with a carbon tax of 50 €/tCO^2 in Figure 3-2 and with carbon capture technology in Figure 3-3. (no storage costs included). Production costs for wind power are added to this comparison of centralised power options as it may become a cost effective option very soon.

According to the assumptions used for the calculation (evolution of energy prices is determinant), NGCC is the technology that presents the lower electricity production costs in 2000 but expected increase of energy prices for natural gas and low technological progress for coal and gas technologies would equalize nuclear and fossil production costs in 2025 and make combined cycle uneconomic in 2050 (Fig. 3-1).

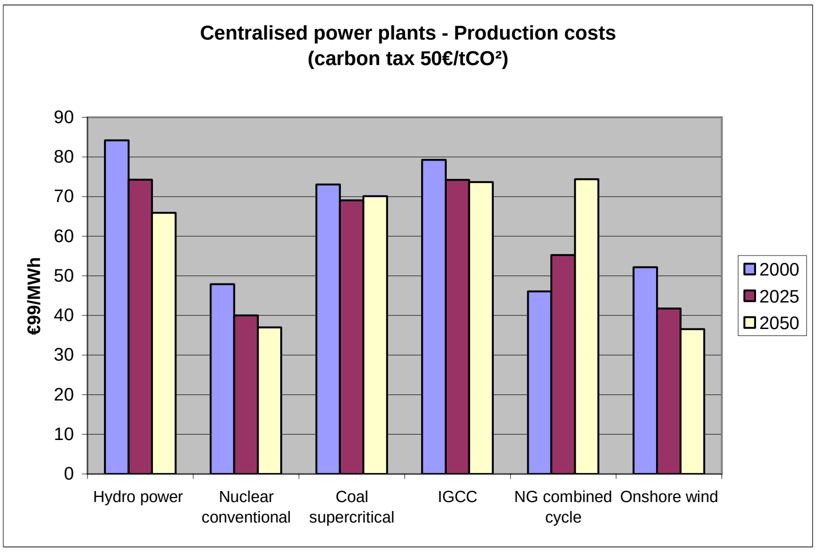
The introduction of a carbon tax logically favours energy sources with a low carbon content. With a carbon tax of 50 €/tCO² and without carbon capture technology, conventional nuclear power plants and NGCC present very similar cost in the first decade, but given rising gas prices NGCC is no more cost competitive in 2025 and beyond. Assumptions on technological progress make onshore wind competitive with nuclear power in 2025. The introduction of carbon capture technology does not change drastically the relative positions of the different options. Conventional coal and IGCC present higher costs than nuclear and wind but would probably contribute to the production mix. Production costs for NGCC are very similar in 2025 but again assumptions regarding gas price rise disqualify the technology in 2050.

Figure 3-1: Production costs – centralised power plants



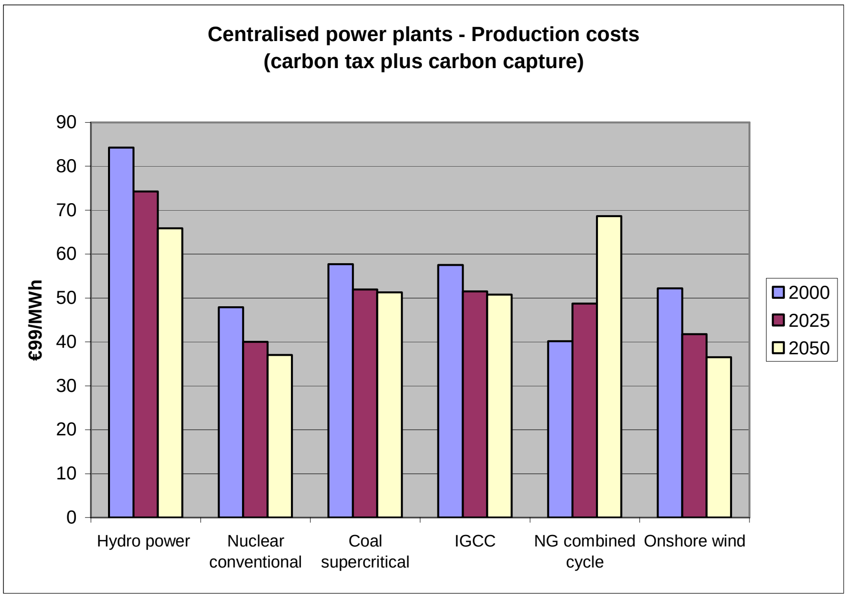
Source: Techpol

Figure 3-2: Production costs – centralised power plants – carbon tax



Source: Techpol

Figure 3-3: Production costs – centralised power plants with carbon capture – carbon tax

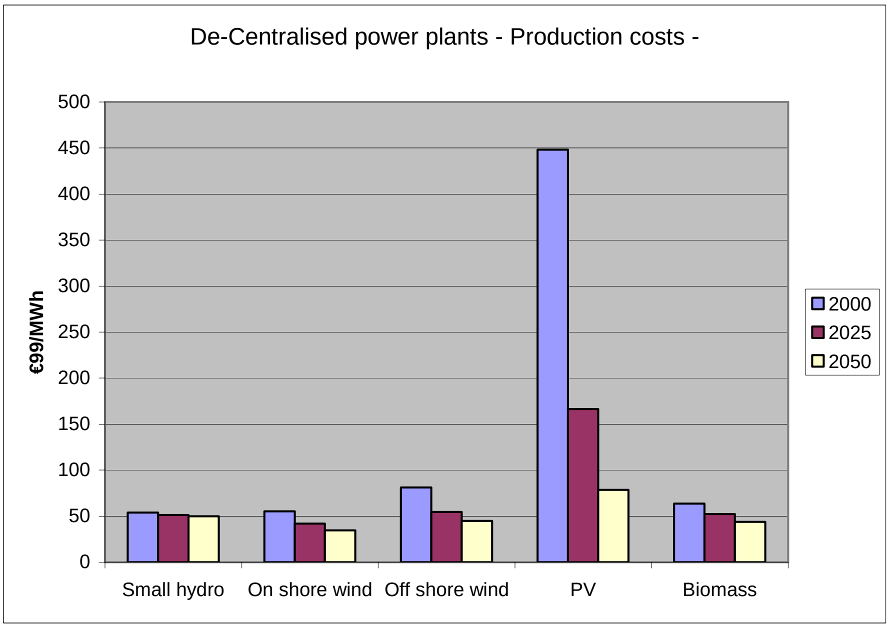


Source: Techpol

3.1.3. KWh Cost comparison – De-centralised power plants

Being independent of energy prices, the electricity production costs from decentralised (renewable) power plants may appear more robust than the production costs from fossil fuel power plants, in 2025 and a fortiori in 2050. They are mostly situated in a range between 40 and 50 €/MWh in 2050 but large uncertainties still remain regarding specific technologies (construction costs for small hydro power plants may vary significantly according to the site) and for variable or fixed O&M costs.

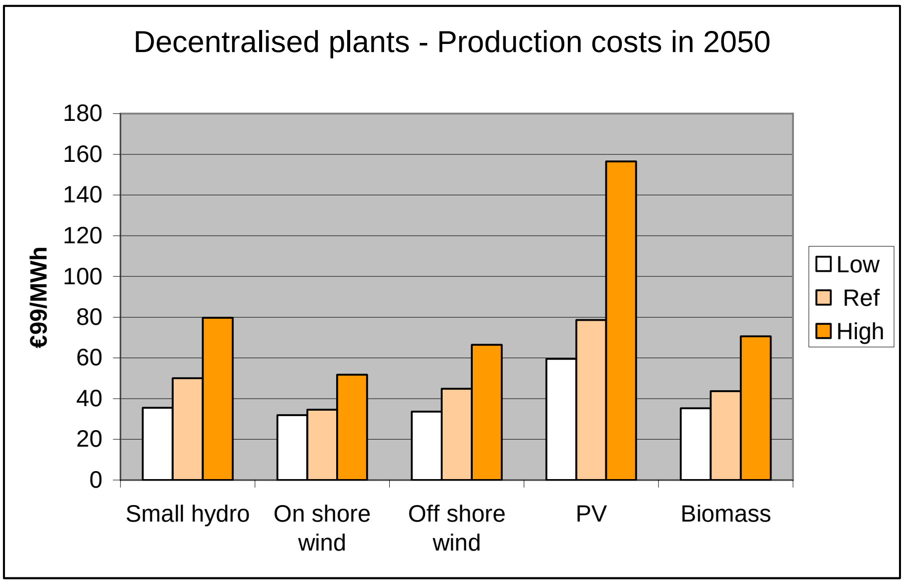
Figure 3-4: Production costs - De-centralised power plants



Source: Techpol

Introduction of uncertainty margins illustrate this problem. The gap between lower and higher production costs is much larger for two technologies, small hydro and PV, which are particularly sensible to site conditions and/or uncertainties regarding O&M costs.

Figure 3-5: Production costs including uncertainty margins



Source: Techpol

The variations in costs considered here do only refer to uncertainties relative to investment, O&M costs or efficiency. Indeed complementary uncertainties that are mostly specific to renewable / decentralised energy sources should be added over “conventional” uncertainties on production costs: grid reinforcement costs and/or incremental costs incurred by intermittent sources. The cost effectiveness of decentralised power plants and their contribution to the production mix could as a result be very different according to the magnitude of these costs.

3.2. Hydrogen production costs

Hydrogen production costs are calculated using a similar discounting approach as for electricity production costs. Seven technologies (9 when including CO_2 Capture and Storage options) have been considered for hydrogen production:

- Gas steam reforming
- Coal partial oxidation
- Biomass pyrolysis
- High temperature – Solar thermochemical cycle
- High temperature – Nuclear thermochemical cycle
- Electrolysis – Wind dedicated
- Electrolysis – Nuclear dedicated

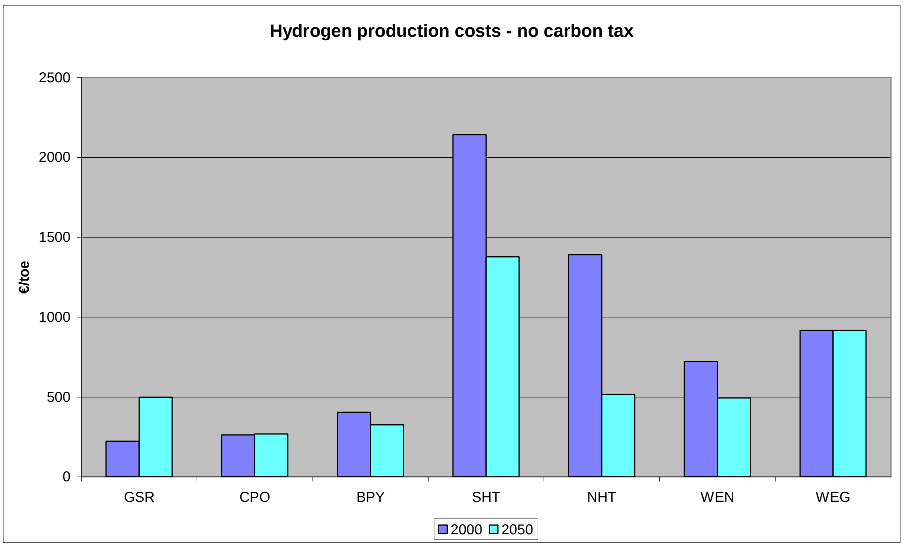
3.2.1. Hydrogen production – no carbon tax

Detailed assumptions used to estimate hydrogen production costs are presented in Table 3-1. According to these assumptions, hydrogen production costs from gas steam reforming and coal partial oxidation are very similar in 2000, in the range of 220 - 260 €/toe (5 - 6 €/GJ). Biomass pyrolysis could be another option in a near future. The other technologies could not become cost-effective until 2050. By that time, high temperature thermochemical cycle using nuclear power and water electrolysis could present production costs close to gas steam reforming (due partly to natural gas price increases), but biomass pyrolysis and coal partial oxidation would remain the most cost-effective option. According to our assumptions, water electrolysis using electricity from grid is not cost effective even in 2050. We have considered that low electricity costs are required which implies off-peak hours and lower availability factor. With less restrictive conditions, production costs from water electrolysis would improve but still remain clearly higher than other technologies except when using electricity from a dedicated nuclear power plant (or wind power plant).

Table 3-1: Hydrogen production costs: main parameters

		GSR		CPO		BPY		SHT		NHT		WEN		WEG		WEW	
€ 2 000		**2000**	**2050**	**2000**	**2050**	**2000**	**2050**	**2000**	**2050**	**2000**	**2050**	**2000**	**2050**	**2000**	**2050**	**2000**	**2050**
Investment Cost (overn.)	€/M3d	42	38	107	65	112	80	410	289	735	229	362	250	118	100	251	193
Technical lifetime	Years	25	25	35	35	35	35	35	35	25	25	25	25	25	25	25	25
Construction time	Years	3	3	3	3	3	3	4	4	8	8	8	8	3	3	8	8
Annualised fixed. cost																	
Capital cost	€/M3d/y	4,36	3,95	10,14	6,16	10,62	7,58	39,21	27,63	91,06	27,26	43,19	29,42	12,26	10,39	29,13	22,20
FOM cost	€/M3d/y	0,26	0,24	0,97	0,58	5,60	4,00	19,64	14,23	10,00	10,00	4,69	3,00	1,37	0,82	4,69	4,14
Availability factor	%	90%	90%	90%	90%	80%	90%	29%	32%	80%	85%	80%	85%	30%	30%	28%	28%
Fixed cost	€/toe	**55**	**50**	**132**	**80**	**216**	**137**	**2143**	**1377**	**1347**	**467**	**638**	**407**	**363**	**299**	**1288**	**1003**
Variable cost																	
Fuel price	€/toe	120,0	360	57	100	100	100	0	0	20	25	20	25	400	450	0	0
Carbon price	€/tCO2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fuel efficiency	%	74%	81%	59%	65%	65%	65%	100%	100%	45%	50%	31%	37%	75%	75%	100%	100%
VOM cost	€/toe	6	6	35	35	35	35	0	0	0	0	20	20	21	21	0	0
Variable cost	**€/toe**	**168**	**450**	**132**	**189**	**189**	**189**	**0**	**0**	**45**	**50**	**84**	**87**	**554**	**621**	**0**	**0**
Production cost	€/toe	**223**	**500**	**263**	**269**	**405**	**326**	**2143**	**1377**	**1391**	**517**	**722**	**494**	**918**	**920**	**1288**	**1003**
Production cost	€/GJ	5	12	6	6	10	8	51	33	33	12	17	12	22	22	31	24

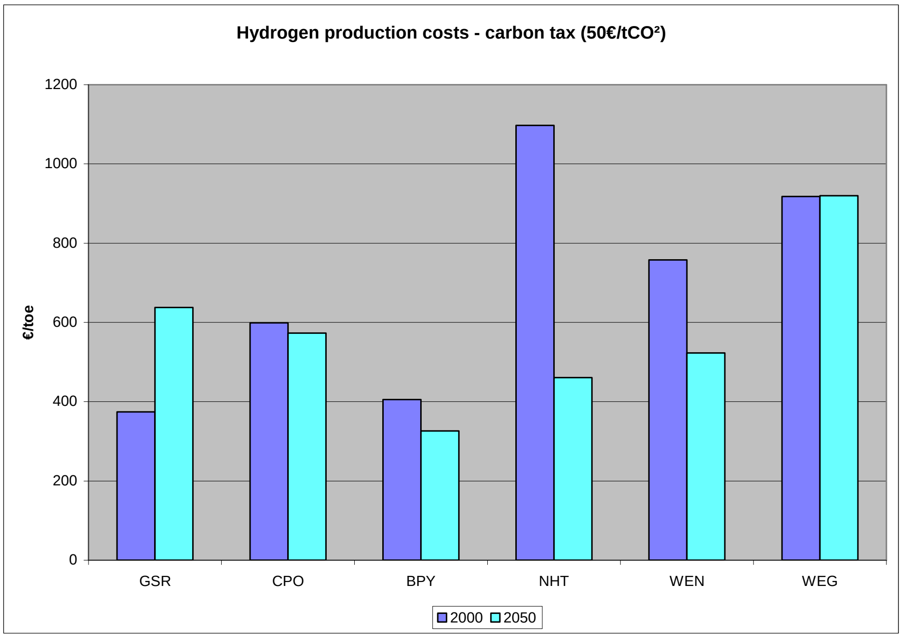
Figure 3-6: Hydrogen production costs: 2000 – 2050



3.2.2. Hydrogen production – carbon tax and carbon capture

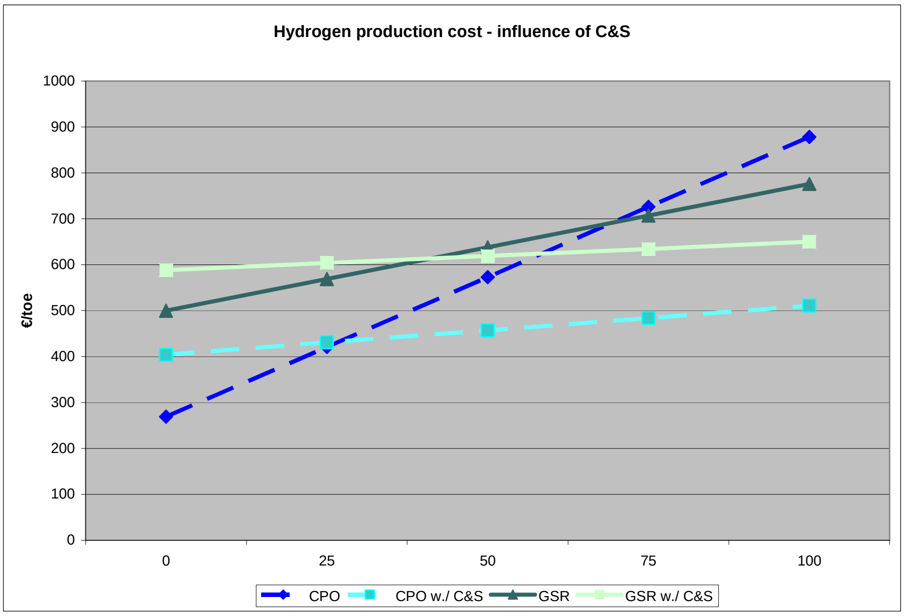
The introduction of a uniform CO_2 tax of 50 €/tCO_2 influences gas steam reforming and coal partial oxidation production costs. The increase in GSR production costs is 67% in 2000 and 28% in 2050 (the impact of a uniform carbon tax is less important in 2050 given the increase of gas prices), and 128% and 113% respectively for CPO (Figure 3-7). The CO_2 tax raises the hydrogen production cost to the range of 375 - 600 €/toe in 2000 for the less expensive three technologies and 325 - 575 €/toe in 2050. With such a level of carbon tax, it would be less expensive to integrate CO_2 Capture and Storage technology than paying the tax (Figure 3-8); the threshold level of carbon tax above which the CCS technology become cost effective is 25 € for coal and 40-45 € for gas.

Figure 3-7: H_2 production costs – CO_2 tax



Source: Techpol

Figure 3-8: H_2 production costs as a function of CO_2 tax level



Source: Techpol

With CCS technology, gas steam reforming is still cost effective in 2000 but biomass pyrolysis is clearly the most interesting technology in 2050 for hydrogen production according to the assumptions used for the calculation (no price increase for biomass feedstock). Three other technologies may participate to the hydrogen production mix, among which coal partial oxidation with carbon capture. With a 50 €/tCO² the hydrogen production costs may lie in a range of 325 - 525 €/toe.

3.3. Road passenger transport costs

A similar approach has been used in order to compare future transport costs for different road passenger vehicles. Six different technologies have been considered representing the most probable competing technologies for road transport vehicles in the future:

- conventional vehicle (internal combustion engine)
- "pluggable" hybrid vehicle
- electric vehicle
- H_2 powered internal combustion engine
- Fuel cell vehicle – H_2
- Fuel cell vehicle – natural gas

The different technologies are compared on the basis of the global transport cost including investment, O&M and fuel costs, expressed in €/km. In order to differentiate the technological progress on the different components of the vehicle, the investment cost has been divided in three parts:

- motor
- storage / reformer
- body

Average fuel consumption of the conventional vehicle has been estimated to be 7l/100 km with a progression of 5% on each period of 25 years. Fuel consumption and improvements in performance of competing vehicles are estimated in reference to the consumption of the conventional vehicle and similarly for O&M costs. The main parameters used for the calculation are presented in Table 3-2 .

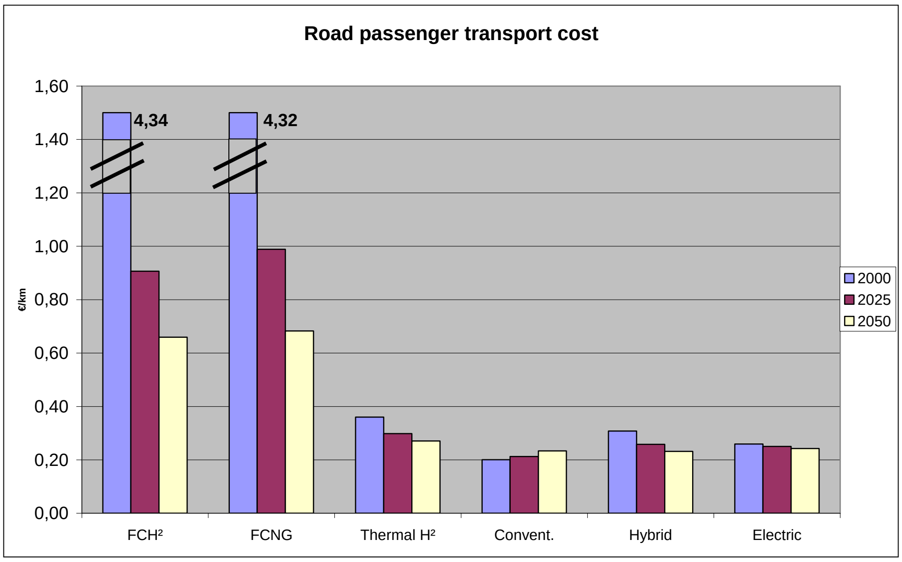
Table 3-2: Road passenger vehicle transport costs – Main parameters

USA fuel prices		**FCH^2**			**FCNG**			**Thermal H^2**			**Convent.**			**Hybrid**			**Electric**		
		2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050
Capacity	kW/veh	40	40	40	40	40	40	80	80	80	80	80	80	50	50	50	60	60	60
Engine cost	€/kW	11000	1500	750	11000	1500	750	80	60	40	40	40	40	150	120	90	60	40	30
Reformer/storage	€/kW	20	18	16	60	54	49	20	18	16	0	0	0	30	27	24	120	108	97
Shadow user cost index		1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0
Engine/stor./ref. cost	€/Veh.	440800	60720	30640	442400	62160	31960	8000	6240	4496	3200	3200	3200	9000	7350	5700	10800	8880	7620
Body cost	€/Veh.	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000
Total veh. Cost (incl.SUC)	€/veh.	455800	75720	45640	457400	77160	46960	23000	21240	19496	18200	18200	18200	24000	22350	20700	25800	23880	22620
Floor cost	*€/veh.*		*22800*			*23500*			*14600*			*16400*			*15500*			*17000*	
Fuel input	tep/100km	0,0033	0,003025	0,00275	0,0055	0,00495	0,0044	0,0055	0,005225	0,00495	0,0055	0,005225	0,00495	0,0044	0,003575	0,00275	0,0033	0,003025	0,00275
Consumpt. (/conv.)	%	60,00%	55,00%	50,00%	100,00%	90,00%	80,00%	100,00%	95,00%	90,00%	100,00%	95,00%	90,00%	80,00%	65,00%	50,00%	60,00%	55,00%	50,00%
Fuel cost	€/tep	1700	1150	882	418	459	664	1700	1150	882	383	505	794	1272	1258	1353	1710	1628	1628
Util. Factor	km/yr	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000	15000
O&M	€/yr	410	273	137	410	273	137	328	273	273	273	273	273	328	273	205	137	137	137
Lifetime	yrs	11	13	15	11	13	15	11	12	12	12	12	12	11	13	15	13	14	15
		8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%
Total cost	€/km	4,34	0,69	0,39	4,32	0,69	0,40	0,33	0,27	0,23	0,20	0,21	0,22	0,30	0,25	0,21	0,28	0,25	0,23
Total cost (incl. SUC)	€/km	***4,34***	***0,69***	***0,39***	***4,32***	***0,69***	***0,40***	***0,33***	***0,27***	***0,23***	***0,20***	***0,21***	***0,22***	***0,30***	***0,25***	***0,21***	***0,28***	***0,25***	***0,23***

Source: Techpol

According to the assumptions used (energy prices and trends are presented for USA) the present transport costs are 0.20 €/km for conventional vehicles. These costs should increase to 0.22 €/km in 2050 assuming almost a doubling of oil prices. In 2050, the cost of road passenger vehicles – with comparable road-fuel tax hypotheses – would stand between 0.21 and 0.23 €/km for conventional, hybrid, electric and thermal H_2 vehicles. By that time, hybrid vehicles should be competitive with conventional vehicles. Burning hydrogen in internal conventional engine vehicles could also be competitive depending on the delivery cost of hydrogen. Electric vehicles would not be strictly cost effective because of assumptions used on electricity prices and on road-fuel taxes, but they would stand very near to the other vehicle costs. On the other hand, fuel-cell vehicles using either hydrogen or natural gas would still present much higher costs given present assumptions of fuel-cell costs.

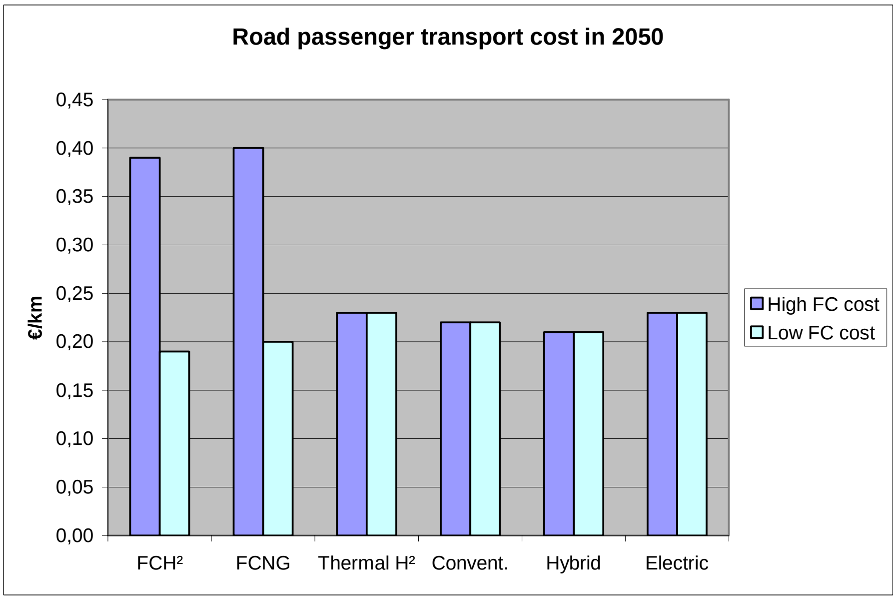
__Figure 3-9: Road passenger transport cost__



Source: Techpol

According to present assumptions in TECHPOL, fuel cell cost would be near 750 €/kw in 2050 which is not enough to be competitive with other road passenger transport vehicles. When more optimistic prospects regarding technological progress are considered, the results are totally different (Figure 3-10). Assuming a cost of 100 €/kW for fuel cells in 2050 instead of 750 €/kW radically improves fuel cell vehicles transport costs. The range of road passenger vehicle transport cost narrows to 0.20 - 0.23 €/km and in that case all technologies lie in a very narrow range between 0.19 and 0.23 €/km.

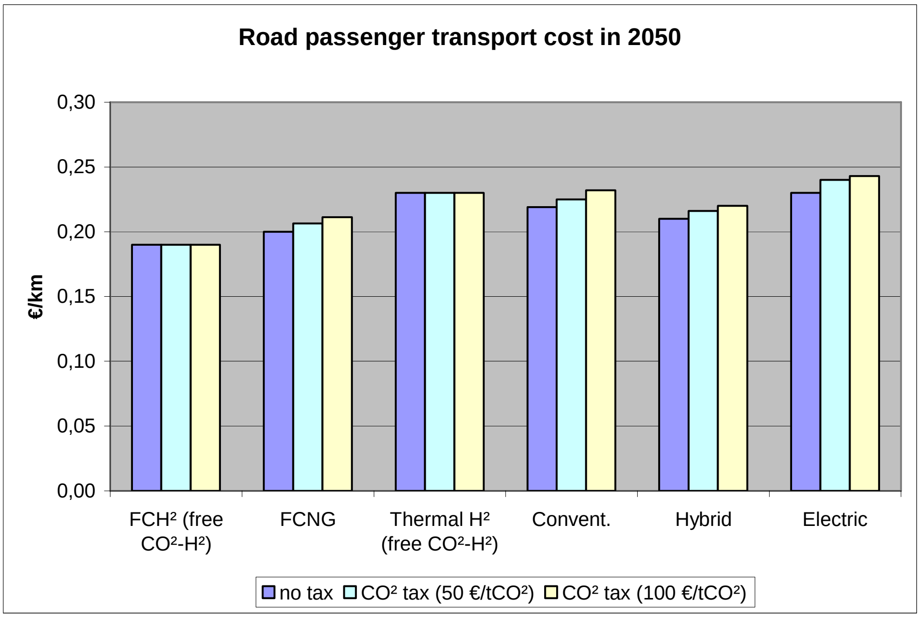
__Figure 3-10: Influence of fuel cell costs on transport costs in 2050__



Source: Techpol

Finally, it is important to notice that the introduction of a CO_2 tax would not have a strong influence on relative transport costs. In Figure 3-11, three different levels of CO_2 tax have been simulated with the optimistic assumptions on fuel-cell prices maintained. Hydrogen production is supposed to be carbon free and do not suffer from the introduction of the carbon tax. On the other hand, the costs of fossil fuel powered vehicles such as conventional and hybrid do increase, just as fuel-cell vehicles powered by natural gas and electric vehicles if electricity is not produced by carbon-free energy sources. The result is surprisingly not sensitive to the carbon tax level, even when high figures such as 100 €/tCO² are considered. With a carbon tax of 100 €/tCO², the cost of conventional, hybrid and electric vehicles increases slightly which narrows the gap with hydrogen powered FC vehicles. But, with or without a carbon tax, no technology really emerges for road passenger vehicles in 2050.

Figure 3-11: Influence of CO_2 tax on transport costs



ANNEX: Key Data Sets

COAL POWER PLANTS – Pulverised Coal – w./o Capture and Storage

Investment costs

Steam boiler - Coal

Data in €99 / $ 02

Home

Data	Comments	C&S	Country/F	Designation	Designation (	Referen	Source	Source (detailed)	Yea	data prod.	Units	1990	2000	2010	2020	2030	2040	2050
Investment cost			Belgium	Pulverised Coal	Supercritical	600 MW	Commission Ampere, 2000	Rapport de la Commi	2000	original data	$03/kW		1321,9					
Investment cost			Belgium	Pulverised Coal	Ultra-supercritic	600 MW	Commission Ampere, 2000	Rapport de la Commi	2000	original data	$03/kW				1462			
Investment cost			EU 15	Pulverised coal	Ultra-supercritical		ECN, 1997	CO^2 Abatement in W	1997	original data	€00/kW	1471	1470,6	*1471*	1471	*1471*	1471	
Investment cost			EU 15	coal fired conventional			ECN, 2003	Smekens et al., Cont	2002	original data	$03/kW		1150,9					
Investment cost			EU 15	Coal supercritical			ECN, 2003	Smekens et al., Cont	2002	original data	$03/kW		1278,8					
Investment cost	Interests during construction are		USA	Pulverized coal		600 MW	EIA, 2004	Assumptions for the	2003	original data	$03/kW			1167	1131			
Investment cost	Interest during construction is no		EU-15	Coal conventional - CCT			EPE - Sapientia		2004	original data	€00/kW		1286	1245	1204	1163	1121	1080
Investment cost	Interest during construction is no		EU 15	Pulverised coal	Supercritical		EPE - Sapientia		2004	original data	€00/kW		1543,3	1419,9	1296	1194	1111	1029
Investment cost			USA	Coal		400 MW	GENSIM, 2002	Electricity generatior	2002	from DOE	$03/kW							
Investment cost			USA	Coal		400 MW	GENSIM, 2002	Electricity generatior	2002	from Platt's	$03/kW							
Investment cost			OECD	Coal,	Ultra-supercritical		IEA b, 2004	Gielen & Podkanski,	2004	original data	$03/kW				1289			
Investment cost			OECD	Coal, steam cycle			IEA b, 2004	Gielen & Podkanski,	2004	original data	$03/kW			1100	1049			
Investment cost			Europe	Steam boiler - coal fired			IEA, 2004	Assumptions for the	2004	original data	$03/kW		1176	1063	962	962		
Investment cost			Canada	Pulverized coal	Super critical	450 MW	IEA, 2005	Projected Costs of G	2005		€00/kW			1320				
Investment cost			OECD	Pulverised Coal			IEA, GHG R&D, 2002,	Freund & Davison, G	2002	from EPRI	$03/kW		1218					
Investment cost			OECD	Pulverised Coal		500 MW	IEA, GHG R&D, 2002,	Freund & Davison, G	2002	from IEA GHG	$03/kW		1090					
Investment cost			OECD	Standard coal pow er plant			IIASA, 2004	Riahi et al., Technolo	2000	diff. Sources	$03/kW		0					
Investment cost			Germany	Coal steam pow er production		600 MW	Ikarus, 2003		2000	original data	€00/kW		920	915	930	920		
Investment cost			EU 15	Coal	Supercritical	650 MW	IPTS		2000	average	€00/kW	1695	1044,3	1062,8	1066	1070		
Investment cost			EU 15	Pulverized coal		> 500 MW	IPTS		2000	average	€00/kW	1240	1066,9	1066,9	1067	1067		
Investment cost			Belgium	Pulverised coal	Ultra-supercritic		Markal - BEL, 2001	The Belgian Markal d	2001	original data	€00/kW	1188	952,43					
Investment cost			France	Pulverized coal	Supercritical	2 x 800 MW	MINEFI, 2003	DGEMP - DIDEME, Co	2003	original data	€00/kW			1187,2				
Investment cost			OECD	Pulverised Coal			MIT, 2001	David & Herzog, The	2000	diff. Sources	$03/kW		1229	1180				
Investment cost	The reference year is not precis		UK	Pulverized coal	Supercritical	1600 MW	RAE, 2004	The cost of generati	2004	original data	€00/kW							
Investment cost	overnight cost		USA	Coal steam elec	Supercritical	500 MW	Williams, 2004	IGCC,	2004	original data	$03/kW		1222					
Investment cost	overnight cost		USA	Coal steam elec	Ultra-supercritic	500 MW	Williams, 2004	IGCC,	2004	original data	$03/kW		1241					
Investment cost	Costs data include all capital cos		USA	Pulverized coal	Supercritical	600 MW	US NCEP, 2004	National Commission	2004	from NorthBric	$03/kW							

COAL POWER PLANTS – Pulverised Coal – w. Capture and Storage

Investment costs

Steam boiler - Coal

Data in €99 / $ 02

Home

Data	Comments	C&S	Country/R	Designation	Designation (	Referen	Source	Source (detailed)	Yea	data prod.	Units	1990	2000	2010	2020	2030	2040	2050
Investment cost		Yes - Chemical	OECD	Coal,	Ultra-supercritical		IEA b, 2004	Gielen & Podkanski,	2004	original data	$02/kW					1714		
Investment cost		Yes - Chemical	OECD	Coal, steam cycle			IEA b, 2004	Gielen & Podkanski,	2004	original data	$02/kW			1893	1760			
Investment cost		Yes - post comb	OECD	Pulverised Coal			IEA, GHG R&D, 2002,	Freund & Davison, G	2002	from EPRI	$02/kW		2116					
Investment cost		Yes - post comb	OECD	Pulverised Coal		500 MW	IEA, GHG R&D, 2002,	Freund & Davison, G	2002	from IEA GHG	$02/kW		1988					
Investment cost		Yes - post comb	OECD	Standard coal power plant			IIASA, 2004	Riahi et al., Technolo	2000	diff. Sources	$02/kW		0					
Investment cost		Yes - MEA scru	OECD	Pulverised Coal			MIT, 2001	David & Herzog, The	2000	diff. Sources	$02/kW		2234	1902				
Investment cost	overnight cost	Yes	USA	Coal steam elec	Supercritical	500 MW	Williams, 2004	IGCC,	2004	original data	$02/kW		2117					
Investment cost	overnight cost	Yes	USA	Coal Ultra-super	Ultra-supercritic	500 MW	Williams, 2004	IGCC,	2004	original data	$02/kW		2077					

COAL POWER PLANTS – IGCC – w./o. Capture and Storage
Investment costs

IGCC - Coal

Data in €99 / $ 02

Home

	Comments	C&S	Country	Designation	Designation (	Reference S	Source	Source (deta	Year	data prod.	Units	1990	2000	2010	2020	2030	2040	2050
Investment cost			Belgium	IGCC		260 MW	Commission Am	Rapport de la Co	2000	original data	$03/kW			1884	1786	1687		
Investment cost			EU 15	IGCC			ECN, 1997	CO² Abatement	1997	original data	€00/kW		1573	1573	1573	1573	1573	
Investment cost			EU 15	IGCC			ECN, 2003	Smekens et al.,	2002	original data	$03/kW		1345	1345	1345	1345		
Investment cost	incl. cont. Factors & tech optim.,		USA	IGCC		550 MW	EIA, 2004	Assumptions fo	2003	original data	$03/kW			1376	1273			
Investment cost	incl. cont. Factors & tech optim.,		USA	IGCC		550 MW	EIA, 2004	Assumptions fo	2003	original data	$03/kW			2136				
Investment cost	incl. cont. Factors & tech optim.,		USA	IGCC		550 MW	EIA, 2005	Assumptions fo	2004	original data	$03/kW							
Investment cost			EU-15	IGCC			EPE - Sapientia		2004	original data	€00/kW		1955	1852	1749	1605	1420	1235
Investment cost			OECD	IGCC			IEA b, 2004	Gielen & Podkan	2004	original data	$03/kW			1455	1260			
Investment cost			Europe	IGCC			IEA, 2004	Assumptions fo	2004	original data	$03/kW		1603	1450	1311	1186		
Investment cost			OECD	IGCC	Slurry feed, H-c		IEA, GHG R&D, 2	Freund & Daviso	2002	from EPRI	$03/kW		1347					
Investment cost			OECD	IGCC	Dry feed, F-clas		IEA, GHG R&D, 2	Freund & Daviso	2002	from IEA GHG	$03/kW		1571					
Investment cost			Germany	IGCC		450 MW	Ikarus, 2003		2000	original data	€00/kW			1125	1115	1110		
Investment cost			EU-15	IGCC		> 500 MW	IPTS		2004	original data	€00/kW			1139	1083	1027		
Investment cost			Belgium	IGCC			Markal - BEL, 20	The Belgian Mar	2001	original data	€00/kW			1358				
Investment cost			OECD	IGCC			MIT, 2001	David & Herzog,	2000	diff. Sources	$03/kW		1497	1269				
Investment cost			UK	IGCC		480	RAE, 2004	The cost of gen	2004	original data	€00/kW			1543	1543			
Investment cost	cost data include all capital cost		USA	IGCC		600 MW	US NCEP, 2004	National Commis	2004	from NorthBric	$03/kW							
Investment cost	overnight cost		USA	IGCC		500 MW	US NCEP, 2004	Williams, IGCC, N	2004	original data	$03/kW		1350					
Investment cost			Canada	Pulverized coal	Super critical	450 MW	IEA, 2005	Projected Costs	2005		€00/kW			1366				
Investment cost			Germany	IGCC	desulphurisatior	450 MW	IEA, 2005	Projected Costs	2005	original data	€00/kW			1129				

COAL POWER PLANTS – IGCC – w. Capture and Storage
Investment costs

IGCC - Coal

Data in €99 / $ 02

Home

	Comments	C&S	Country	Designation	Designation (	Reference S	Source	Source (deta	Year	data prod.	Units	1990	2000	2010	2020	2030	2040	2050
Investment cost		Y- Input fuel capture (Selexo		IGCC w ith input capture			ECN, 2003	Smekens et al.,	2002	original data	$03/kW			1770				
Investment cost		Y - Upstream se	OECD	IGCC			IEA b, 2004	Gielen & Podkan	2004	original data	$03/kW			2100	1635			
Investment cost		Yes - pre-comb	OECD	IGCC	Slurry feed, H-c		IEA, GHG R&D, 2	Freund & Daviso	2002	from EPRI	$03/kW		1753					
Investment cost		Yes - pre-comb	OECD	IGCC	Dry feed, F-clas		IEA, GHG R&D, 2	Freund & Daviso	2002	from IEA GHG	$03/kW		2351					
Investment cost		Yes - upstream	OECD	IGCC			MIT, 2001	David & Herzog,	2000	diff. Sources	$03/kW		2040	1639				
Investment cost	overnight cost	Yes	USA	IGCC		500 MW	US NCEP, 2004	Williams, IGCC, N	2004	original data	$03/kW		1755					
Investment cost		Yes -	Germany	IGCC	desulphurisatior	425 MW	IEA, 2005	Projected Costs	2005	original data	€00/kW			1412				

COMBINED CYCLE POWER PLANTS – w./o Capture and Storage

Investment costs

Combined Cycle Gas Turbine - Natural Gas (STAG)

Data in €99 / $ 02

Home

Data	Comments	C&S	Country/F	Designation	Designation (	Reference S	Source	Source (deta	Year	data prod.	Units	1990	2000	2010	2020	2030	2040	2050
Investment cost			Belgium	Gaz turbine, combined cycle		460 MW	Commission Am	Rapport de la C	2000	original data	$03/kW			562	562	562		
Investment cost			EU 15	STAG pow er plant			ECN, 1997	CO^2 Abatement	1997	original data	€00/kW	763,8	764	764	764	764	764	
Investment cost			EU 15	Gas CC			ECN, 2003	Smekens et al.,	2002	original data	$03/kW		522	522	522	522		
Investment cost	Interests during construction are		USA	Conv gas/oil CC	Commissioning (	400 MW	EIA, 2004	Assumptions fo	2003	original data	$03/kW			546	533			
Investment cost	Interests during construction are		USA	Convent. Gas/oil Combined Cycle		250 MW	EIA, 2005	Assumptions fo	2004	original data	$03/kW							
Investment cost	Interest during construction is no		EU 15	Gas in GT w ith CC - GGC			EPE- Sapientia -		2004	original data	€00/kW		514	504	560	548	537	525
Investment cost			USA	Gas CC		400 MW	GENSIM, 2002	Electricity gener	2002	from DOE	€00/kW							
Investment cost			USA	Gas CC		400 MW	GENSIM, 2002	Electricity gener	2002	from Platt's	€00/kW							
Investment cost			OECD	Nat Gas CC			IEA b, 2004	Gielen & Podkan	2004	original data	$03/kW			*400*				
Investment cost			Europe	GT - nat gaz			IEA, 2004	Assumptions fo	2004	original data	$03/kW		534	509	483	460		
Investment cost	The reference y		OECD	Natural gaz combined cycle			IEA, GHG R&D,	Freund & Daviso	2000	EPRI	$03/kW		545					
Investment cost	The reference y		OECD	Natural gaz combined cycle			IEA, GHG R&D,	Freund & Daviso	2000	IEA GHG R&D	$03/kW		438					
Investment cost			OECD	Natural gaz combined cycle			IIASA, 2004	Riahi et al., Tech	2000	diff. Sources	$03/kW		0					
Investment cost			Germany	Combined gaz and steam pow er		400 MW (00) - 5	Ikarus, 2003		2000	original data	€00/kW		460	435	430	425		
Investment cost			Germany	Combined gaz and steam pow er		800 MW (00) - 1	Ikarus, 2003		2000	original data	€00/kW		410	395	390	385		
Investment cost			EU 15	GTCC		> 350 MW	IPTS		2000	original data	€00/kW	652,3	463	434	434	434		
Investment cost			Belgium	STAG pow er plant			Markal - BEL, 20	The Belgian Mar	2001	original data	€00/kW		405	405				
Investment cost			France	CC gaz	Commissioning (	2 x 400 MW	MINEFI, 2003	DGEMP - DIDEMI	2003	original data	€00/kW			490				
Investment cost	The reference year is not precis		OECD	Natural gaz combined cycle			MIT, 2001	David & Herzog,	2000	diff. Sources	$03/kW		579	564				
Investment cost	The reference year is not precis		UK	gas turbines - heavy duty - Coml		800 MW	RAE, 2004	The cost of gen	2004	original data	€00/kW							
Investment cost	overnight cost		USA	Nat Gas CC		400 MW	Williams, 2004	IGCC,	2004	original data	$03/kW		530					
Investment cost	Costs data include all capital cos		USA	NGCC		600 MW	US NCEP, 2004	National Commis	2004	from NorthBric	$03/kW							

-

COMBINED CYCLE POWER PLANTS – w. Capture and Storage

Investment costs

Combined Cycle Gas Turbine - Natural Gas (STAG)

Data in €99 / $ 02

Home

Data	Comments	C&S	Country/F	Designation	Designation (	Reference S	Source	Source (deta	Year	data prod.	Units	1990	2000	2010	2020	2030	2040	2050
Investment cost		Yes		NGCC w ith flue gas capture			ECN, 2003	Smekens et al.,	2002		$03/kW			1146				
Investment cost		Yes	OECD	Nat Gas CC			IEA b, 2004	Gielen & Podkan	2004	original data	$03/kW			*800*	*800*			
Investment cost	The reference y	Yes	OECD	Natural gaz combined cycle			IEA, GHG R&D,	Freund & Daviso	2000	EPRI	$03/kW		1079					
Investment cost	The reference y	Yes	OECD	Natural gaz combined cycle			IEA, GHG R&D,	Freund & Daviso	2000	IEA GHG R&D	$03/kW		844					
Investment cost		Yes	OECD	Natural gaz combined cycle			IIASA, 2004	Riahi et al., Tech	2000	diff. Sources	$03/kW		0					
Investment cost	The reference y	Yes	OECD	Natural gaz combined cycle			MIT, 2001	David & Herzog,	2000	diff. Sources	$03/kW		1083	977				
Investment cost	overnight cost	Yes	USA	Nat Gas CC		400 MW	Williams, 2004	IGCC,	2004	original data	$03/kW		1008					

NUCLEAR POWER PLANTS – Generation III

Investment costs

Nuclear - gen. 3

Data in €00 / $ 03

Home

Data	Comments	Count	Designation	Designation (de	Referenc	Source	Source (deta	Year	data prod.	Units	1990	2000	2010	2020	2030	2040	2050
Investment cost		Belgium	PWR		1300 MW	Commission Am	Rapport de la C	2000	original data	$03/kW			1912	1870	1828		
Investment cost		Belgium	AP600 (passive nuclear pp based on PWR)			Commission Am	Rapport de la C	2000	original data	$03/kW			2334	2222	2109		
Investment cost	Interest during	EU 15	LWR			ECN, 1997	CO² Abatement	1997	original data	€00/kW	2782	2782	2782	2782	2782	2782	
Investment cost		EU 15	Fission LWR			ECN, 2003	Smekens et al.,	2002	original data	€00/kW		2130					
Investment cost		EU 15	nuclear fission -	Fission Gas cooled reactor		ECN, 2003	Smekens et al.,	2002	original data	€00/kW			1759				
Investment cost	incl. cont. Fact	USA	Adv LWR - 1000 MW			EIA, 2004	Assumptions fo	2003	original data	$03/kW			1857	1686			
Investment cost	incl. cont. Fac	USA	Adv. Nuclear		1000 MW	EIA, 2005	Assumptions fo	2004	original data	$03/kW							
Investment cost	Interest during	EU-15	2nd / 3rd gen			EPE - Sapientia		2004	original data	€00/kW		1982	1833	1684	1546	1417	1288
Investment cost		USA	Nuclear		600 MW	GENSIM, 2002	Electricity gener	2002	from DOE	$03/kW							
Investment cost		Europe	nuclear			IEA, 2004	Assumptions fo	2004	original data	$03/kW		1817	1817	1817	1817		
Investment cost		EU 15	Nuclear		1000/1500	IPTS		2000	original data	€00/kW		1749					
Investment cost		EU 15	Nuclear		1000/1500	IPTS		2000	original data	€00/kW		2264					
Investment cost		Belgium	PWR nuclear plant			Markal - BEL, 20	The Belgian Mar	2001	original data	€00/kW	1439						
Investment cost	Interest during	France	EPR -	10 units	1600 MW -	MINEFI, 2003	DGEMP - DIDEM	2003	original data	€00/kW							
Investment cost	MIT estimate -	UK	nuclear fission -	EPR or LWR or adv	1000 MW	RAE, 2004	The cost of gen	2004	original data	€00/kW							
Investment cost		Canada	Pressurised Heavy w ater reacto		1400 MW	IEA, 2005	Projected Costs	2005	original data	$03/kW			1373				
Investment cost		USA	Generation III		1000 MW	IEA, 2005	Projected Costs	2005	original data	$03/kW			1894				
Investment cost		Finland	PWR		1500 MW	IEA, 2005	Projected Costs	2005	original data	€00/kW			1559				
Investment cost		Germany	PWR		1590 MW	IEA, 2005	Projected Costs	2005	original data	€00/kW			1458				
Investment cost		Netherlan	PWR		1600 MW -	IEA, 2005	Projected Costs	2005	original data	€00/kW			1764				
Investment cost		Romania	Pressurised Heavy w ater reacto		665 MW	IEA, 2005	Projected Costs	2005	original data	€00/kW			1484				

CONCENTRATING SOLAR POWER PLANTS

Investment costs

Concentrating solar power

Data in €00 / $ 03

Home

Data	Comments	Country / Reg	Designation	Designation (	Reference si	Source	Source (deta	Year	Data prod.	Units	1990	2000	2010	2020	2030	2040	2050
Investment cost		EU 15	solar thermal power			ECN, 2003	Smekens et al.,	2002	original data	$03/kW		2210					
Investment cost	incl. contingency	USA	Solar Thermal		100 MW	EIA, 2004	Assumptions fo	2003	original data	$03/kW			2515	2244			
Investment cost	incl. contingency	USA	Solar Thermal		100 MW	EIA, 2005	Assumptions fo	2004	original data	$03/kW			2563	2309			
Investment cost		EU-15	thermo solar			EPE - Sapientia		2004	original data	$03/kW		3500	3267	3033	2800	2567	2333
Investment cost	incl. contingency	USA	Solar Thermal		100 MW	GENSIM, 2002	Electricity gener	2002	from DOE	$03/kW							
Investment cost	incl. contingency	USA	Solar Thermal		100 MW	GENSIM, 2002	Electricity gener	2002	from Platt's	$03/kW							
Investment cost		EU 15	Concentrating solar power - Parabolic dish			IEA, 2003	Renewables for	2003	original data - fr	€00/kW			3071	1152			
Investment cost		EU 15	Concentrating solar power - Power tower			IEA, 2003	Renewables for	2003	original data - fr	€00/kW			2015	1056			
Investment cost		EU 15	Concentrating solar power - Parabolic trough			IEA, 2003	Renewables for	2003	original data - fr	€00/kW			2111	1343			
Investment cost	High assumption	EU 15	Concentrating s	Generic technology		IEA, 2003	Renewables for	2003	original data - fr	€02/kW			3838				
Investment cost	Low assumption	EU 15	Concentrating s	Generic technology		IEA, 2003	Renewables for	2003	original data - fr	€02/kW			1919				
Investment cost		EU-15	Solar thermal			IEA, 2004	Assumptions fo	2004	original data	€00/kW		2750	2362	2075	1691		
Investment cost		EU 15	Sol therm elec - hybrid NG fuelled			IPTS		2000	original data	€00/kW		2572	1857	2006			

PHOTOVOLTAIC POWER PLANTS

Investment costs

Photovoltaics

Data in €00 / $ 03

Home

Data	Comments	Country / Re(	Designation	Designation (	Reference si	Source	Source (deta	Year	Data pro	Units	1990	2000	2010	2020	2030	2040	2050
Investment cost		USA	PV indiv./single home basis - 20		2,6 kWp (00) - 3	DOE, 1997	EERE - Renew a	1997	original c	$03/kW		7071	4018	2334	1358		
Investment cost		EU-15	PV system Middle Eur			ECN, 1997	CO² Abatement	1997	original c	€00/kW		5700	2257	1739	1220	1060	
Investment cost		EU 15	PV grid connected			ECN, 2003	Smekens et al.,	2003	original c	$03/kW		4972					
Investment cost		EU 15	PV roof integrated			Ecofys, 2001	Economic Evalu	2001	original c	€00/kW			3125				
Investment cost	incl. contingency	USA	PV - reference			EIA, 2004	Assumptions fo	2004	original c	$03/kW			3769	3082			
Investment cost	incl. cont. Facto	USA	Photovoltaic		5 MW	EIA, 2005	Assumptions fo	2005	original c	$03/kW							
Investment cost		EU-15	PV	building integrated - DPV		EPE - Sapientia		2004	original c	$03/kW		6173	4733	3292	2366	1955	1543
Investment cost		USA	PV		5 MW	GENSIM, 2002	Electricity gener	2002	from DO	$03/kW							
Investment cost		USA	PV		5 MW	GENSIM, 2002	Electricity gener	2002	Platt's	$03/kW							
Investment cost		EU-15	Photovoltaic			IEA, 2004	Assumptions fo	2004	original c	€00/kW		6140	3510	3033	2572		
Investment cost		OECD	Photovoltaic			IEA, 2004	Assumptions fo	2004	average	€00/kW		6226	3321	2864	2428		
Investment cost		Germany	PV system		2 kWp	Ikarus		2003	average	€00/kW		7127	6400	5850			
Investment cost		Germany	PV system		20 kWp	Ikarus		2003	average	€00/kW		6336	5700	5100			
Investment cost		EU 15	PV in buildings			IPTS		2000	original c	€00/kW	10289	7202	4630				
Investment cost	Interest during c	France	PV residential - rooftop		5 kW	MINEFI, 2003	DGEMP - DIDEM	2003	original c	€00/kW			6105				
Investment cost	Interest during c	France	PV residential - rooftop		5 kW	MINEFI, 2003	DGEMP - DIDEM	2003	original c	€00/kW			4343				

WIND POWER PLANTS – OFF SHORE

Investment costs

Wind off-shore

Data in €00 / $ 03

Home

Data	Comments	Country / Re(	Designation	Designation (	Reference si	Source	Source (deta	Year	Data pro	Units	1990	2000	2010	2020	2030	2040	2050
Investment costs		EU 15	wind off-shore			ECN, 1997	CO² Abatement	1997	original c	€00/kW		1995	1995	1995	1995	1995	
Investment costs		EU 15	Wind offshore			ECN, 2003	Smekens et al.,	2003	original c	$03/kW		1657					
Investment costs		EU 15	offshore wind turbine			Ecofys, 2001	Economic Evalu	2001	original c	€00/kW			1749				
Investment costs		EU 15	offshore windfarm			EPE - Sapientia		2004	original c	€00/kW		1801	1605	1410	1214	1019	823
Investment costs		EU-15	wind off-shore			IEA, 2004	Assumptions fo	2004	original c	€00/kW		1600	1140	981	938		
Investment costs		OECD	wind off-shore			IEA, 2004	Assumptions fo	2004	original c	€00/kW		1541	1079	927	886		
Investment costs		Germany	offshore wind		2 MW (10) - 5 M	Ikarus		2003	average	€00/kW			1842	1656			
Investment costs		EU 15	wind		1 MW	IPTS		2000	average	€00/kW		1981	1543	1415	1286		
Investment costs	MIT estimate - to	UK	offshore wind farm		36 x 3,6 MW	RAE, 2004	The cost of gen	2004	MIT estin	€00/kW			1330	1203			
Investment costs		EU 15	offshore windfarm			VLEEM, 2002	Final report, anr	2002	original c	€00/kW			1379	1229	1143		

WIND POWER PLANTS – ON SHORE

Investment costs

Wind on-shore

Data in €00 / $ 03

Home

Data	Comments	Country / Reg	Designation	Designation (	Reference si	Source	Source (deta	Year	Data pro	Units	1990	2000	2010	2020	2030	2040	2050
Investment cost		USA	advanced horiz. axis wind turbin		Turbine size 1 M	DOE, 1997	EERE - Renew a	1997	original c	$03/kW		842	758	735	713		
Investment cost		EU-15	wind on-shore			ECN, 1997	CO^2 Abatement	1997	original c	€00/kW	1300	980	952	923	923	923	
Investment cost		EU 15	Wind on-shore		large	ECN, 2003	Smekens et al.,	2003	original c	$03/kW		829					
Investment cost		EU 15	Wind on-shore		small	ECN, 2003	Smekens et al.,	2003	original c	$03/kW		921					
Investment cost		EU 15	on shore wind turbines			Ecofys, 2001	Economic Evalu	2001	original c	€00/kW		1250	875				
Investment cost	incl. contingency	USA	Wind - reference			EIA, 2004	Assumptions fo	2004	original c	$03/kW			1034	1024			
Investment cost	incl. cont. Facto	USA	Wind		50 MW	EIA, 2005	Assumptions fo	2005	original c	$03/kW			1130	1127			
Investment cost		EU-15	wind -onshore			EPE - Sapientia		2004	original c	$03/kW		1167	1085	1003	922	840	758
Investment cost		USA	wind		50 MW windfarr	GENSIM, 2002	Electricity gener	2002	from DO	$03/kW							
Investment cost		USA	wind		50 MW windfarr	GENSIM, 2002	Electricity gener	2002	Platt's	$03/kW							
Investment cost		EU-15	wind on-shore			IEA, 2004	Assumptions fo	2004	original c	€00/kW		1020	828	737	706		
Investment cost		OECD	wind on-shore			IEA, 2004	Assumptions fo	2004	average	€00/kW		983	784	696	666		
Investment cost		Germany	wind on-shore		1,5 MW (99) - 2	Ikarus		2003	original c	€00/kW		1324	1188	1080			
Investment cost	average cost fo	EU 15	wind		1 MW	IPTS		2000	original c	€00/kW		1003	741	648	556		
Investment cost	Interest during c	France	onshore wind turbines		unit size : 2 MW	MINEFI, 2003	DGEMP - DIDEM	2003	original c	€00/kW			753				
Investment cost	MIT estimate - to	UK	onshore wind farm		12 x 2 MW	RAE, 2004	The cost of gen	2004	MIT estin	€00/kW			1072	972			
Investment cost		EU	wind on-shore			VLEEM, 2002	Final report, anr	2002	original c	€00/kW		900	726	637	589		

BIOMASS POWER PLANTS

Investment costs

Biomass - gaseification / Gas turbine - direct combustion

Data in €00 / $ 03

Home

Data	Comments	Country / Reg	Designation	Designation (	Reference si	Source	Source (deta	Year	Data pro	Units	1990	2000	2010	2020	2030	2040	2050
Investment cost	Includes enginee	USA	Direct gasification CC		75 MW (00) - 10	DOE, 1997	EERE - Renew a	1997	original d	$03/kW		2123	1643	1412	1111		
Investment cost	Includes enginee	USA	Direct combustion		50 MW (00) - 10	DOE, 1997	EERE - Renew a	1997	original d	$03/kW		1959	1511	1251	1115		
Investment cost		EU 15	biomass fired conventional			ECN, 2003	Smekens et al.,	2003	original d	$03/kW		1637					
Investment cost		EU 15	biomass IGCC			ECN, 2003	Smekens et al.,	2003	original d	$03/kW			1944				
Investment cost	incl. contingency	USA	Biomass - reference			EIA, 2004	Assumptions fo	2004	original d	$03/kW			1710	1566			
Investment cost	incl. contingency	USA	Biomass			EIA, 2004	Assumptions fo	2004	original d	$03/kW							
Investment cost	incl. contingency	USA	Biomass		80 MW	EIA, 2005	Assumptions fo	2005	original d	$03/kW							
Investment cost		EU-15	Biomasse Gazéification - TAG (BGT)			EPE - Sapientia		2004	données	$03/kW		2333	2217	2100	1983	1867	1750
Investment cost		OECD	Biomass IGCC			IEA b, 2004	Gielen & Podkar	2004	original d	$03/kW				2400			
Investment cost		EU-15	Bioenergy			IEA, 2004	Assumptions fo	2004	original d	€00/kW		2375	2138	2020	1914		
Investment cost		industrialisés	Bioenergy			IEA, 2004	Assumptions fo	2004	original d	€00/kW		2288	2023	1908	1807		
Investment cost		EU 15	Biomass gasif CC<25 MW			IPTS		2000	données	€00/kW		2064	1913	1795	1677		
Investment cost		Belgium	Wood gasification power plant			Markal - BEL, 20	The Belgian Mar	2001	original d	€00/kW		1140					
Investment cost		UK	Biomass fired Fluidized bed combustion			RAE, 2004	The cost of gen	2004	original d	€00/kW							

ELECTRICITY PRODUCTION COSTS (1)

Large Scale Power Techonlogies		**Large hydro**			Large hydro - Unfav. hypoth.			Large hydro - Fav. hypoth.			**Nuclear (convent.)**			Nuclear (convent.) - Unfav. hypoth.			Nuclear (convent.) - Fav. hypoth.			**Nuclear (gen IV)**			Nuclear (gen IV) - Unfav. hypoth.			Nuclear (gen IV) - Fav. hypoth.		
99€ - 95$		2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050
Floor costs		1800			1900			1000			1400			1600			1000			900			3000			900		
Overn. Inv. Cost	€/kW	2600	2300	2000	3000	2600	2200	1500	1250	1200	1950	1800	1600	2100	1950	1800	1250	1200	1150	6000	5000	1200	6000	5000	4000	6000	5000	1200
Other costs	€/kW										200	150	150	200	150	150	200	150	150	200	200	150	200	200	150	200	200	150
Technical lifetime	Years	45	45	45	45	45	45	40	40	40	40	40	40	40	40	40	50	50	50	40	40	40	40	40	40	40	40	40
Construction time	Years	8	8	8	8	8	8	8	8	8	10	8	8	10	8	8	10	8	8	12	10	8	12	10	8	12	10	8
Interest rate	%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Decommission share	%	10%	10%	10%	10%	10%	10%	10%	10%	10%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%
Discount rate (%)	%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%
Total investment Cc	**€/kW**	3227	2855	2482	3723	3227	2731	1864	1554	1491	2797	2442	2187	2997	2633	2442	1840	1654	1592	8555	6860	1678	8555	6860	5242	8555	6860	1678
Fixed cost	**€/kWy**	267	236	205	308	267	226	156	130	125	235	205	183	251	221	205	150	135	130	717	575	141	717	575	440	717	575	141
FOM cost	€/kWy	51	44	44	90	68	45	30	25	20	60	51	50	60	60	60	50	48	45	60	40	20	60	60	60	60	40	20
Load. Factor	%	43%	43%	43%	40%	40%	40%	50%	50%	50%	80%	85%	85%	80%	85%	85%	80%	85%	85%	80%	80%	85%	80%	80%	85%	80%	80%	85%
Fixed cost	**€/MWh**	84	74	66	113	95	77	43	35	33	42	34	31	44	38	36	29	25	24	111	88	22	111	91	67	111	88	22
Fuel price	**€/toe**										20	22	25	20	22	25	20	22	25	20	22	25	20	22	25	20	22	25
Carbon content	tCO2/toe																											
Carbon price	**€/tCO2**																											
Fuel efficiency	%	100%	100%	100%	100%	100%	100%	100%	100%	100%	34%	38%	39%	34%	38%	39%	34%	38%	39%	30%	35%	45%	30%	35%	40%	30%	35%	45%
Fuel cost incl. Carbc	**€/MWh**										5,1	5,0	5,5	5,1	5,0	5,5	5,1	5,0	5,5	5,7	5,4	4,8	5,7	5,4	5,4	5,7	5,4	4,8
VOM cost	€/MWh	0,0	0,0	0,0	0,4	0,4	0,4	0,2	0,2	0,2	1,2	0,8	0,6	1,2	0,8		1,2	0,8	0,6	3,0	2,0	1,0	3,0	2,0	1,0	3,0	2,0	1,0
Variable cost	**€/MWh**	0,0	0,0	0,0	0,4	0,4	0,4	0,2	0,2	0,2	6,3	5,8	6,1	6,3	5,8	5,5	6,3	5,8	6,1	8,7	7,4	5,8	8,7	7,4	6,4	8,7	7,4	5,8
Production cost	**€/MWh**	84	74	66	114	96	78	43	36	33	48	40	37	51	43	41	35	30	30	120	95	27	120	98	73	120	95	27

New and Renewable Power Gen		**Cogeneration (ICE - industry)**			Cogen indus - Unfav. hypoth.			Cogen indus - Fav. hypoth.			**Small hydro**			Small hydro - Unfav. hypoth.			Small hydro - Fav. hypoth.			**Wind on-shore**			Wind onshore. - Unfav. hypoth.			Wind onshore. - Fav. hypoth.		
99€ - 95$		2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050
Floor costs		500			700			400			1400			2100			1000			600			600			400		
Overn. Inv. Cost	€/kW	800	650	600	1000	900	800	700	600	500	2100	2000	1950	3000	2900	2800	1500	1450	1400	1000	800	700	1250	1000	800	900	750	650
Other costs	€/kW																											
Technical lifetime	Years	15	15	15	15	15	15	15	15	15	30	30	30	30	30	30	40	40	40	20	20	20	20	20	20	25	25	25
Construction time	Years	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1
Interest rate		5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Decommission share		5%	5%	5%	5%	5%	5%	5%	5%	5%	20%	20%	20%	20%	20%	20%	20%	20%	20%	5%	5%	5%	20%	20%	20%	20%	20%	20%
Discount rate (%)		8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%
Total investment Cc	**€/kW**	853	693	639	1066	959	853	746	639	533	2300	2190	2135	3285	3176	3066	1627	1572	1518	1061	848	742	1365	1092	874	971	809	701
Fixed cost	**€/kWy**	100	81	75	125	112	100	87	75	62	204	195	190	292	282	272	136	132	127	108	86	76	139	111	89	91	76	66
FOM cost	€/kWy	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	2,0	31,5	30,0	29,3	45,0	43,5	42,0	30,0	29,0	28,0	20,0	16,0	14,0	31,3	25,0	20,0	18,0	15,0	13,0
Load. Factor	%	90%	90%	90%	90%	90%	90%	90%	90%	90%	50%	50%	50%	50%	50%	50%	50%	50%	50%	28%	28%	28%	20%	22%	25%	28%	28%	28%
Fixed cost	**€/MWh**	12,9	10,5	9,7	16	14	13	11	10	8	53,8	51,3	50,0	76,9	74,3	71,8	38,0	36,7	35,5	52,2	41,8	36,5	97,2	70,7	49,8	44,4	37,0	32,1
Fuel price	**€/toe**	120	200	360	120	200	360	120	200	360																		
Carbon content	tCO2/toe	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2																		
Carbon price	**€/tCO2**	0	0	0	0	0	0	0	0	0																		
Fuel efficiency	%	85%	87%	88%	85%	87%	88%	85%	87%	88%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Electrical efficiency	%	40%	41%	42%	40%	41%	42%	40%	41%	42%																		
Thermal efficiency	%	45%	46%	46%	45%	46%	46%	45%	46%	46%																		
Fuel cost incl. Carbc	**€/MWh**	25,8	42,0	73,7	25,8	42,0	73,7	25,8	42,0	73,7	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
VOM cost	€/MWh	13	12	11	16,0	15,0	14,0	13	12	11																		
Variable cost	**€/MWh**	25,9	32,5	47,0	28,9	35,5	50,0	25,9	32,5	47,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Production cost	**€/MWh**	39	43	57	45	50	63	37	42	55	54	51	50	77	74	72	38	37	35	52	42	37	97	71	50	44	37	32

ELECTRICITY PRODUCTION COSTS (2)

Large Scale Power Techonlogies		**Lignite conventional**			*Lignite conventional - Unfav. hypoth.*			*Lignite conventional - Fav. hypoth.*			**Coal conventional**			*Coal conventional - Unfav. hypoth.*			*Coal conventional - Fav. hypoth.*			**Pulverised coal (supercr.)**			*Pulverised coal (supercr.) - Unfav. hypoth.*			*Pulverised coal (supercr.) - Fav. hypoth.*		
99€ - 95$		2000	2025	2050	*2000*	*2025*	*2050*	*2000*	*2025*	*2050*	2000	2025	2050	*2000*	*2025*	*2050*	*2000*	*2025*	*2050*	2000	2025	2050	*2000*	*2025*	*2050*	*2000*	*2025*	*2050*
Floor costs		800			900			900			800			900			900			600			900			800		
Overn. Inv. Cost	€/kW	1100	1000	950	1200	1150	1100	1100	1050	1000	1100	1000	950	1200	1150	1100	1100	1050	1000	1200	1050	900	1300	1150	1000	1000	950	900
Other costs	€/kW																											
Technical lifetime	Years	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35
Construction time	Years	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	3	3	3	3
Interest rate	%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Decommission share	%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Discount rate (%)	%	8%	8%	8%	*8%*	*8%*	*8%*	*8%*	*8%*	*8%*	8%	8%	8%	*8%*	*8%*	*8%*	*8%*	*8%*	*8%*	8%	8%	8%	*8%*	*8%*	*8%*	*8%*	*8%*	*8%*
Total investment Cc	**€/kW**	**1248**	**1135**	**1078**	1362	1305	1248	1248	1192	1135	**1248**	**1135**	**1078**	1362	1305	1248	1248	1192	1135	**1330**	**1164**	**997**	1441	1275	1108	1108	1053	997
Fixed cost	**€/kWy**	**107**	**97**	**93**	117	112	107	107	102	97	**107**	**97**	**93**	117	112	107	107	102	97	**114**	**100**	**86**	124	109	95	95	90	86
FOM cost	€/kWy	55	50	48	60	58	55	55	53	50	55	50	48	60	58	55	55	53	50	40	38	36	45	42	40	40	38	36
Load. Factor	%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%
Fixed cost	**€/MWh**	**22**	**20**	**19**	24	23	22	22	21	20	**22**	**20**	**19**	24	23	22	22	21	20	**21**	**19**	**16**	23	20	18	18	17	16
Fuel price	**€/toe**	**38**	**48**	**67**	38	48	67	38	48	67	**57**	**71**	**100**	57	71	100	57	71	100	**57**	**71**	**100**	57	71	100	57	71	100
Carbon content	tCO2/toe	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0
Carbon price	**€/tCO2**	**0**	**0**	**0**	0	0	0	0	0	0	**0**	**0**	**0**	0	0	0	0	0	0	**0**	**0**	**0**	0	0	0	0	0	0
Fuel efficiency	%	35%	37%	38%	34%	35%	36%	36%	37%	38%	38%	39%	40%	36%	37%	38%	38%	39%	40%	44%	48%	50%	43%	46%	48%	44%	48%	50%
Fuel cost incl. Carb	**€/MWh**	**9,4**	**11,1**	**15,1**	9,6	11,7	15,9	9,1	11,1	15,1	**12,8**	**15,6**	**21,7**	13,7	16,6	22,6	12,8	15,6	21,7	**11,2**	**12,7**	**17,2**	11,4	13,4	17,9	11,2	12,7	17,2
VOM cost	€/MWh	2,5	2,5	2,5	2,5	2,5	2,5	2,0	2,0	2,0	2,5	2,5	2,5	2,5	2,5	2,5	2,0	2,0	2,0	2,5	2,5	2,5	2,5	2,5	2,5	2,0	2,0	2,0
Variable cost	**€/MWh**	**11,9**	**13,6**	**17,6**	12,2	14,2	18,5	11,1	13,1	17,1	**15,3**	**18,1**	**24,2**	16,2	19,1	25,2	14,8	17,6	23,7	**13,7**	**15,2**	**19,7**	14,0	15,9	20,4	13,2	14,7	19,2
Production cost	**€/MWh**	**34**	**33**	**36**	36	37	40	33	34	37	**37**	**38**	**43**	40	42	47	37	38	44	**34**	**34**	**36**	37	36	39	31	32	36

New and Renewable Power Gen		**Wind off-shore**			*Wind offshore. - Unfav. hypoth.*			*Wind offshore - Fav. hypoth.*			**Concentrating solar**			*Concentrating solar - Unfav. hypoth.*			*Concentrating solar - Fav. hypoth.*			**Photovoltaic**			*Photovoltaic - Unfav. hypoth.*			*Photovoltaic - Fav. hypoth.*		
99€ - 95$		2000	2025	2050	*2000*	*2025*	*2050*	*2000*	*2025*	*2050*	2000	2025	2050	*2000*	*2025*	*2050*	*2000*	*2025*	*2050*	2000	2025	2050	*2000*	*2025*	*2050*	*2000*	*2025*	*2050*
Floor costs		600			900			600			900			1500			700			1100			1500			700		
Overn. Inv. Cost	€/kW	1750	1000	800	2000	1500	1200	1500	1000	800	2750	2100	1800	3500	2500	2000	2500	1500	1000	6000	2500	1500	9000	5000	2000	4500	2000	1000
Other costs	€/kW																											
Technical lifetime	Years	20	20	20	15	15	15	20	20	20	25	25	25	25	25	25	25	25	25	25	30	30	25	25	25	25	30	30
Construction time	Years	2	2	2	1	1	1	1	1	1	3	3	3	3	3	3	3	3	3	1	1	1	1	1	1	1	1	1
Interest rate	%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Decommission share		5%	5%	5%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	20%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Discount rate (%)		8%	8%	8%	*8%*	*8%*	*8%*	*8%*	*8%*	*8%*	8%	8%	8%	*8%*	*8%*	*8%*	*8%*	*8%*	*8%*	8%	8%	8%	*8%*	*8%*	*8%*	*8%*	*8%*	*8%*
Total investment Cc	**€/kW**	**1901**	**1086**	**869**	2227	1670	1336	1639	1092	874	**3111**	**2376**	**2037**	3960	2829	2263	2829	1697	1131	**6385**	**2649**	**1589**	9578	5321	2128	4789	2119	1060
Fixed cost	**€/kWy**	**194**	**111**	**89**	260	195	156	167	111	89	**291**	**223**	**191**	371	265	212	265	159	106	**598**	**235**	**141**	897	498	199	449	188	94
FOM cost	€/kWy	52,5	30	24	60	45	36	37,5	25,0	20,0	27,5	21,0	18,0	35,0	25,0	20,0	25,0	15,0	10,0	30,0	12,5	7,5	90,0	50,0	20,0	45,0	20,0	10,0
Load. Factor	%	35%	35%	35%	33%	33%	33%	37%	37%	37%	25%	27%	28%	22%	23%	25%	25%	27%	28%	17%	18%	19%	15%	15%	16%	17%	18%	19%
Fixed cost	**€/MWh**	**80,3**	**45,9**	**36,7**	110,7	83,1	66,4	63,1	42,0	33,6	**145,7**	**103,0**	**85,1**	210,7	143,9	105,9	132,4	73,6	47,3	**421,8**	**157,1**	**89,3**	751,3	417,4	156,5	331,5	132,1	62,6
Fuel price	**€/toe**																											
Carbon content	tCO2/toe																											
Carbon price	**€/tCO2**																											
Fuel efficiency	%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Electrical efficiency	%																											
Thermal efficiency	%																											
Fuel cost incl. Carb	**€/MWh**	**0,0**	**0,0**	**0,0**	0,0	0,0	0,0	0,0	0,0	0,0	**0,0**	**0,0**	**0,0**	0,0	0,0	0,0	0,0	0,0	0,0	**0,0**	**0,0**	**0,0**	0,0	0,0	0,0	0,0	0,0	0,0
VOM cost	€/MWh																											
Variable cost	**€/MWh**	**0,0**	**0,0**	**0,0**	0,0	0,0	0,0	0,0	0,0	0,0	**0,0**	**0,0**	**0,0**	0,0	0,0	0,0	0,0	0,0	0,0	**0,0**	**0,0**	**0,0**	0,0	0,0	0,0	0,0	0,0	0,0
Production cost	**€/MWh**	**80**	**46**	**37**	111	83	66	63	42	34	**146**	**103**	**85**	211	144	106	132	74	47	**422**	**157**	**89**	751	417	157	331	132	63

ELECTRICITY PRODUCTION COSTS (3)

Large Scale Power Techonlogies		IGCC - Coal			IGCC - Coal - Unfav. hypoth.			IGCC - Coal - Fav. hypoth.			Oil conventional			Oil conventional - Unfav. hypoth.			Oil conventional - Fav. hypoth.			ICE for power gen			ICE for power gen - Unfav. hypoth.			ICE for power gen - Fav. hypoth.		
99€ - 95$		2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050
Floor costs		900			900			700			600			800			600			200			300			200		
Overn. Inv. Cost	€/kW	1500	1350	1200	1600	1400	1300	1300	1100	1000	850	800	750	1000	950	900	800	750	725	434	346	300	500	400	350	434	346	300
Other costs	€/kW																											
Technical lifetime	Years	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	35	25	25	25	25	25	25	25	25	25
Construction time	Years	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	2,5	2,5	2,5	2,5	2,5	2,5	2	2	2
Interest rate	%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Decommission share	%	5%	5%	5%	5%	5%	5%	5%	5%	5%	10%	10%	10%	10%	10%	10%	10%	10%	10%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Discount rate (%)	%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%
Total investment Cc	**€/kW**	1657	1492	1326	1768	1547	1436	1436	1215	1105	942	887	831	1108	1053	997	887	831	804	476	379	329	548	438	384	470	375	325
Fixed cost	**€/kWy**	142	128	114	152	133	123	123	104	95	81	76	71	95	90	86	76	71	69	45	36	31	51	41	36	44	35	30
FOM cost	€/kWy	45	41	36	48	42	39	39	33	30	34	32	30	40	38	36	32	30	29	65	52	45	75	60	53	65	52	45
Load. Factor	%	85%	85%	85%	85%	85%	85%	85%	85%	85%	90%	90%	90%	90%	90%	90%	90%	90%	90%	95%	95%	95%	95%	95%	95%	95%	95%	95%
Fixed cost	**€/MWh**	25	23	20	27	23	22	22	18	17	15	14	13	17	16	15	14	13	12	13	11	9	15	12	11	13	10	9
Fuel price	**€/toe**	57	71	100	57	71	100	57	71	100	183	220	403	183	220	403	183	220	403	183	220	403	183	220	403	183	220	403
Carbon content	tCO2/toe	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0	3,0
Carbon price	**€/tCO2**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fuel efficiency	%	45%	49%	51%	43%	45%	47%	46%	49%	51%	39%	40%	41%	38%	39%	40%	39%	41%	41%	22%	25%	25%	22%	25%	25%	22%	25%	25%
Fuel cost incl. Carbc	**€/MWh**	10,9	12,5	16,9	11,4	13,7	18,3	10,7	12,5	16,9	40,4	47,3	84,6	41,5	48,5	86,7	40,4	46,4	84,6	71,6	77,1	138,7	71,6	77,1	138,7	71,6	77,1	138,7
VOM cost	€/MWh	5,0	4,0	3,0	6,0	5,5	5,0	4,0	3,5	3,0	1,8	1,8	1,8	1,8	1,8	1,8	1,8	1,8	1,8	2,2	2,2	2,2	2,5	2,5	2,5	2,2	2,2	2,2
Variable cost	**€/MWh**	15,9	16,5	19,9	17,4	19,2	23,3	14,7	16,0	19,9	42,2	49,1	86,4	43,3	50,3	88,5	42,2	48,2	86,4	73,7	79,3	140,9	74,1	79,6	141,2	73,7	79,3	140,9
Production cost	**€/MWh**	41	39	40	44	43	45	36	34	37	57	63	99	60	67	104	56	61	99	87	90	150	89	92	152	87	90	150

New and Renewable Power Gen		MSW - biomass convent.			MSW - biomass convent. - Unfav. hypoth.			MSW - biomass convent. - Fav. hypoth.			Biomass gasification			Biomass gasification - Unfav. hypoth.			Biomass gasification - Fav. hypoth.			Fuel Cell - NG			Fuel cell - NG - Unfav. hypoth.			Fuel cell - NG - Fav. hypoth.		
99€ - 95$		2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050
Floor costs		1800			2000			1100			1100			1700			900			100			500			60		
Overn. Inv. Cost	€/kW	2280	2100	2000	2600	2400	2300	1800	1500	1300	2000	1700	1500	2600	2400	2300	1800	1500	1300	11000	1500	750	11000	2500	2000	6000	1250	250
Other costs	€/kW																											
Technical lifetime	Years	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	15	15	15	15	15	15	20	20	20
Construction time	Years	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	0,5	0,5	0,5	1	1	1	1	1	1
Interest rate		5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Decommission share		5%	5%	5%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Discount rate (%)		8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%
Total investment Cc	**€/kW**	2477	2282	2173	2853	2634	2524	1975	1646	1427	2195	1865	1646	2853	2634	2524	1975	1646	1427	11755	1603	801	11755	2671	2137	6350	1323	265
Fixed cost	**€/kWy**	252	232	221	291	268	257	201	168	145	224	190	168	291	268	257	201	168	145	1373	187	94	1373	312	250	647	135	27
FOM cost	€/kWy	45,6	42,0	40,0	52,0	48,0	46,0	27,0	22,5	19,5	60,0	51,0	45,0	52,0	48,0	46,0	27,0	22,5	19,5	275,0	37,5	18,8	330,0	75,0	60,0	90,0	18,8	3,8
Load. Factor	%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	70%	70%	70%	70%	70%	70%	70%	70%	70%
Fixed cost	**€/MWh**	37,8	34,8	33,1	43,5	40,1	38,4	28,9	24,1	20,9	36,0	30,6	27,0	43,5	40,1	38,4	28,9	24,1	20,9	268,8	36,7	18,3	277,8	63,1	50,5	120,1	25,0	5,0
Fuel price	**€/toe**	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	120	200	360	120	200	360	120	200	360
Carbon content	tCO2/toe																			2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2
Carbon price	**€/tCO2**																			0	0	0	0	0	0	0	0	0
Fuel efficiency	%	18%	19%	20%	18%	19%	20%	20%	21%	22%	36%	44%	45%	18%	19%	20%	20%	21%	22%	74%	76%	78%	72%	74%	76%	80%	86%	92%
Electrical efficiency	%																			40%	42%	44%	38%	40%	42%	46%	52%	58%
Thermal efficiency	%																			34%	34%	34%	34%	34%	34%	34%	34%	34%
Fuel cost incl. Carbc	**€/MWh**	47,8	45,3	43,0	47,8	45,3	43,0	43,0	41,0	39,1	23,6	19,7	19,1	47,8	45,3	43,0	43,0	41,0	39,1	13,9	22,6	39,7	14,3	23,2	40,7	12,9	20,0	33,7
VOM cost	€/MWh	3,0	3,0	3,0							3,0	3,0	3,0							10,0	10,0	7,0	10	10	7	10	10	7
Variable cost	**€/MWh**	50,8	48,3	46,0	47,8	45,3	43,0	43,0	41,0	39,1	26,6	22,7	22,1	47,8	45,3	43,0	43,0	41,0	39,1	23,9	32,6	46,7	24,3	33,2	47,7	22,9	30,0	40,7
Production cost	**€/MWh**	89	83	79	91	85	81	72	65	60	63	53	49	91	85	81	72	65	60	293	69	65	302	96	98	143	55	46

ELECTRICITY PRODUCTION COSTS (4)

Large Scale Power Techonlogies 99€ - 95$		NG conventional			*NG conventional - Unfav. hypoth.*			*NG conventional - Fav. hypoth.*			Gaz turbine			*Gaz turbine- Unfav. hypoth.*			*Gaz turbine- Fav. hypoth.*			Gas Turbine Combined Cycle			*GTCC - Unfav. hypoth.*			*GTCC - Fav. hypoth.*		
		2000	2025	2050	*2000*	*2025*	*2050*	*2000*	*2025*	*2050*	2000	2025	2050	*2000*	*2025*	*2050*	*2000*	*2025*	*2050*	2000	2025	2050	*2000*	*2025*	*2050*	*2000*	*2025*	*2050*
Floor costs		700			700			600			200			300			200			300			400			300		
Overn. Inv. Cost	€/kW	900	860	800	950	900	850	850	800	750	350	325	300	400	375	350	300	275	275	450	425	400	550	525	500	400	375	350
Other costs	€/kW																											
Technical lifetime	Years	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25
Construction time	Years	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5	2,5
Interest rate	%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Decommission share	%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Discount rate (%)	%	8%	8%	8%	*8%*	*8%*	*8%*	*8%*	*8%*	*8%*	8%	8%	8%	*8%*	*8%*	*8%*	*8%*	*8%*	*8%*	8%	8%	8%	*8%*	*8%*	*8%*	*8%*	*8%*	*8%*
Total investment Cc	**€/kW**	**986**	**943**	**877**	1041	986	932	932	877	822	**384**	**356**	**329**	438	411	384	329	301	301	**493**	**466**	**438**	603	575	548	438	411	384
Fixed cost	**€/kWy**	**92**	**75**	**82**	98	79	87	87	70	77	**36**	**28**	**31**	41	33	36	31	24	28	**46**	**44**	**41**	56	54	51	41	38	36
FOM cost	€/kWy	27	26	24	29	27	26	26	24	23	18	16	15	20	19	18	15	14	14	18	17	16	22	21	20	16	15	14
Load. Factor	%	85%	85%	85%	85%	85%	85%	85%	85%	85%	29%	29%	29%	29%	29%	29%	29%	29%	29%	90%	90%	90%	90%	90%	90%	90%	90%	90%
Fixed cost	**€/MWh**	**16**	**14**	**14**	17	14	15	15	13	13	**21**	**18**	**18**	24	20	21	18	15	17	**8**	**8**	**7**	10	10	9	7	7	6
Fuel price	**€/toe**	**120**	**200**	**360**	120	200	360	120	200	360	**120**	**200**	**360**	120	200	360	120	200	360	**120**	**200**	**360**	120	200	360	120	200	360
Carbon content	tCO2/toe	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2
Carbon price	**€/tCO2**	**0**	**0**	**0**	0	0	0	0	0	0	**0**	**0**	**0**	0	0	0	0	0	0	**0**	**0**	**0**	0	0	0	0	0	0
Fuel efficiency	%	40%	42%	42%	40%	42%	42%	40%	42%	42%	35%	40%	45%	35%	39%	42%	35%	40%	45%	55%	59%	62%	54%	57%	60%	55%	59%	62%
Fuel cost incl. Carbo	**€/MWh**	**25,8**	**41,0**	**73,7**	25,8	41,0	73,7	25,8	41,0	73,7	**29,5**	**43,0**	**68,8**	29,5	44,1	73,7	29,5	43,0	68,8	**18,8**	**29,4**	**49,9**	19,1	30,2	51,6	18,8	29,4	49,9
VOM cost	€/MWh	1,5	1,5	1,5	2,0	2,0	2,0	1,5	1,5	1,5	1,5	1,5	1,5	1,8	1,8	1,8	1,5	1,5	1,5	1,7	1,7	1,7	1,8	1,8	1,8	1,5	1,5	1,5
Variable cost	**€/MWh**	**27,3**	**42,5**	**75,2**	27,8	43,0	75,7	27,3	42,5	75,2	**31,0**	**44,5**	**70,3**	31,2	45,9	75,5	31,0	44,5	70,3	**20,5**	**31,1**	**51,6**	20,9	31,9	53,4	20,3	30,9	51,4
Production cost	**€/MWh**	**43**	**56**	**89**	45	57	91	42	55	89	**52**	**62**	**88**	56	66	96	49	59	87	**29**	**39**	**59**	31	41	62	28	38	58

New and Renewable Power Gen 99€ - 95$		Fuel cell H^2			*Fuel cell H^2 - Unfav. hypoth.*			*Fuel cell H^2 - Fav. hypoth.*		
		2000	2025	2050	*2000*	*2025*	*2050*	*2000*	*2025*	*2050*
Floor costs		100			500			60		
Overn. Inv. Cost	€/kW	11000	1500	750	11000	2500	2000	6000	1250	250
Other costs	€/kW									
Technical lifetime	Years	15	15	15	15	15	15	20	20	20
Construction time	Years	0,5	0,5	0,5	1	1	1	1	1	1
Interest rate		5%	5%	5%	5%	5%	5%	5%	5%	5%
Decommission share		10%	10%	10%	10%	10%	10%	10%	10%	10%
Discount rate (%)		8%	8%	8%	*8%*	*8%*	*8%*	*8%*	*8%*	*8%*
Total investment Cc	**€/kW**	**11755**	**1603**	**801**	11755	2671	2137	6350	1323	265
Fixed cost	**€/kWy**	**1373**	**187**	**94**	1373	312	250	647	135	27
FOM cost	€/kWy	600,0	25,0	18,0	330,0	75,0	60,0	90,0	18,8	3,8
Load. Factor	%	70%	70%	70%	70%	70%	70%	70%	70%	70%
Fixed cost	**€/MWh**	**321,8**	**34,6**	**18,2**	277,8	63,1	50,5	120,1	25,0	5,0
Fuel price	**€/toe**	**893**	**694**	**518**	893	694	518	893	694	518
Carbon content	tCO2/toe	0,0	0,0	0,0	2,2	2,2	2,2	2,2	2,2	2,2
Carbon price	**€/tCO2**	**0**	**0**	**0**	0	0	0	0	0	0
Fuel efficiency	%	78%	80%	83%	76%	79%	81%	84%	89%	91%
Electrical efficiency	%	42%	46%	50%	40%	45%	48%	48%	55%	58%
Thermal efficiency	%	36%	34%	33%	36%	34%	33%	36%	34%	33%
Fuel cost incl. Carbo	**€/MWh**	**98,5**	**74,6**	**53,7**	101,1	75,5	55,0	91,4	67,1	49,0
VOM cost	€/MWh	7,0	7,0	7,0	7	7	7	7	7	7
Variable cost	**€/MWh**	**105,5**	**81,6**	**60,7**	108,1	82,5	62,0	98,4	74,1	56,0
Production cost	**€/MWh**	**427**	**116**	**79**	386	146	113	219	99	61

HYDROGEN PRODUCTION COSTS (1)

Investment cost		**Reference**			*Unfav. Hypoth.*			*Fav. Hypoth.*		
		2000	2025	2050	2000	2025	2050	2000	2025	2050
Therm. Cycle	€/m3d	**135**	**121,5**	**109,35**	*135*	*121,5*	*109,35*	*135*	*121,5*	*109,35*
Electrolyser	€/m3d	**118**	**105**	**100**	*118*	*105*	*100*	*118*	*105*	*100*

Hydrogen Technologies		**Gas Steam Reforming**			*Gas Steam Reforming - Unfav. Hypoth.*			*Gas Steam Reforming - Fav. Hypoth.*		
€ 2 000		2000	2025	2050	2000	2025	2050	2000	2025	2050
Floor costs		30			20			10		
Overn. Inv. Cost	€/M3d	42	40	38	50	45	42	42	40	38
Overn. Inv. Cost	*€/kW*	336	320	304	400	360	336	336	320	304
Other costs	€/M3d									
Technical lifetime	Years	25	25	25	25	25	25	25	25	25
Construction time	Years	3	3	3	3	3	3	3	3	3
Interest rate		5%	5%	5%	5%	5%	5%	5%	5%	5%
Decommission share		0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
Discount rate (%)		8%	8%	8%	8%	8%	8%	8%	8%	8%
Total investment Co	**€/M3d**	47	44	42	55	50	47	47	44	42
Annualised inv. cost	**€/M3d/y**	4,4	4	4	5,2	5	4	4,4	4	4
FOM cost	€/M3d/y	0,26	0,25	0,24	0,50	0,45	0,42	0,26	0,25	0,24
Load. Factor	%	90%	90%	90%	90%	90%	90%	90%	90%	90%
Fixed cost	**€/toe**	55	52	49,6	67	61	56,7	55	52	49,6
Fuel price	**€/toe**	120	200	360	120	200	360	120	200	360
Carbon content	tCO2/toe	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2
Carbon price	**€/tCO2**	0	0	0	0	0	0	0	0	0
Fuel efficiency	%	74%	78%	81%	72%	74%	77%	74%	78%	81%
Fuel cost incl. Carbo	**€/toe**	162	256	444	167	270	468	162	256	444
VOM cost	€/toe	6	6	6	20	20	20	6	6	6
Variable cost	**€/toe**	168	262	450	187	290	488	168	262	450
Production cost	**€/toe**	223	315	500	254	351	544	223	315	500
Production cost	€/GJ	5	8	12	6	8	13	5	8	12

Hydrogen Technologies		**Coal Partial Oxydation**			*Coal Partial Oxydation - Unfav. Hypoth.*			*Coal Partial Oxydation - Fav. Hypoth.*		
€ 2 000		2000	2025	2050	2000	2025	2050	2000	2025	2050
Floor costs		30			40			30		
Overn. Inv. Cost	€/M3d	107	96	65	150	143	97	107	96	65
Overn. Inv. Cost	*€/kW*	856	768	520	1200	1143	774	856	768	520
Other costs	€/M3d									
Technical lifetime	Years	35	35	35	35	35	35	35	35	35
Construction time	Years	3	3	3	3	3	3	3	3	3
Interest rate		5%	5%	5%	5%	5%	5%	5%	5%	5%
Decommission share		0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
Discount rate (%)		8%	8%	8%	8%	8%	8%	8%	8%	8%
Total investment Co	**€/M3d**	118	106	72	166	158	107	118	106	72
Annualised inv. cost	**€/M3d/y**	10,1	9	6	14,2	14	9	10,1	9	6
FOM cost	€/M3d/y	0,97	0,78	0,58	0,97	0,78	0,58	0,97	0,78	0,58
Load. Factor	%	90%	90%	90%	80%	85%	90%	90%	90%	90%
Fixed cost	**€/toe**	132	117	79,9	202	180	115,5	132	117	79,9
Fuel price	**€/toe**	57	71	100	57	71	100	57	71	100
Carbon content	tCO2/toe	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0
Carbon price	**€/tCO2**	0	0	0	0	0	0	0	0	0
Fuel efficiency	%	59%	63%	65%	59%	63%	65%	59%	63%	65%
Fuel cost incl. Carbo	**€/toe**	97	113	154	97	113	154	97	113	154
VOM cost	€/toe	35	35	35	35	35	35	35	35	35
Variable cost	**€/toe**	132	148	189	132	148	189	132	148	189
Production cost	**€/toe**	264	265	269	334	328	304	264	265	269
Production cost	€/GJ	6	6	6	8	8	7	6	6	6

Hydrogen Technologies		**Biomass Pyrolysis**			*Biomass Pyrolysis - Unfav. Hypoth.*			*Biomass Pyrolysis - Fav. Hypoth.*		
€ 2 000		2000	2025	2050	2000	2025	2050	2000	2025	2050
Floor costs		40			50			30		
Overn. Inv. Cost	€/M3d	112	98	80	165	144	118	112	98	70
Overn. Inv. Cost	*€/kW*	896	784	640	1320	1155	943	896	784	560
Other costs	€/M3d									
Technical lifetime	Years	35	35	35	35	35	35	35	35	35
Construction time	Years	3	3	3	3	3	3	3	3	3
Interest rate		5%	5%	5%	5%	5%	5%	5%	5%	5%
Decommission share		0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
Discount rate (%)		8%	8%	8%	8%	8%	8%	8%	8%	8%
Total investment Co	**€/M3d**	124	108	88	182	160	130	124	108	77
Annualised inv. cost	**€/M3d/y**	10,6	9	8	15,6	14	11	10,6	9	7
FOM cost	€/M3d/y	5,60	4,90	4,00	11,55	10,11	8,25	1,31	1,05	0,79
Load. Factor	%	80%	85%	90%	80%	85%	90%	80%	85%	90%
Fixed cost	**€/toe**	216	178	137,2	362	298	230,1	159	130	87,9
Fuel price	**€/toe**	100	100	100	100	100	100	100	100	100
Carbon content	tCO2/toe									
Carbon price	**€/tCO2**									
Fuel efficiency	%	65%	65%	65%	65%	65%	65%	69%	70%	72%
Fuel cost incl. Carbo	**€/toe**	154	154	154	154	154	154	145	143	139
VOM cost	€/toe	35	35	35	35	35	35	35	35	35
Variable cost	**€/toe**	189	189	189	189	189	189	180	178	174
Production cost	**€/toe**	405	367	326	551	487	419	339	308	262
Production cost	€/GJ	10	9	8	13	12	10	8	7	6

HYDROGEN PRODUCTION COSTS (2)

Investment cost		**Reference**			*Unfav. Hypoth.*			*Fav. Hypoth.*		
		2000	2025	2050	*2000*	*2025*	*2050*	*2000*	*2025*	*2050*
Therm. Cycle	€/m3d	**135**	**121,5**	**109,35**	*135*	*121,5*	*109,35*	*135*	*121,5*	*109,35*
Electrolyser	€/m3d	**118**	**105**	**100**	*118*	*105*	*100*	*118*	*105*	*100*

Hydrogen Technologies		**Solar HT - Thermochemical Cycle**			*Solar HT - Therm. Cycle - Unfav. Hypoth.*			*Solar HT - Therm. Cycle - Fav. Hypoth.*			**Nuclear HT - Thermochemical Cycle**			*Nuclear HT - Therm. Cycle - Unfav. Hypoth.*			*Nuclear HT - Therm. Cycle - Fav. Hypoth.*			**Electrolysis - Nuclear**			*Electrolysis - Nuclear - Unfav. Hypoth.*			*Electrolysis - Nuclear - Fav. Hypoth.*		
€ 2 000		2000	2025	2050	*2000*	*2025*	*2050*	*2000*	*2025*	*2050*	2000	2025	2050	*2000*	*2025*	*2050*	*2000*	*2025*	*2050*	2000	2025	2050	*2000*	*2025*	*2050*	*2000*	*2025*	*2050*
Floor costs		60			*60*			*40*			40			*100*			*40*			100			*400*			*100*		
Overn. Inv. Cost	€/M3d	**341**	**279**	**244**	*398*	*309*	*259*	*323*	*234*	*184*	**585**	**497**	**199**	*585*	*497*	*409*	*585*	*497*	*199*	**362**	**330**	**250**	*381*	*349*	*600*	*274*	*255*	*250*
Overn. Inv. Cost	*€/kW*	*2730*	*2232*	*1955*	*3180*	*2472*	*2075*	*2580*	*1872*	*1475*	*4680*	*3972*	*1595*	*4680*	*3972*	*3275*	*4680*	*3972*	*1595*	*2894*	*2640*	*2000*	*3044*	*2790*	*4800*	*2194*	*2040*	*2000*
Other costs	€/M3d																											
Technical lifetime	Years	35	35	35	*35*	*35*	*35*	*35*	*35*	*35*	25	25	25	*25*	*25*	*25*	*25*	*25*	*25*	25	25	25	*25*	*25*	*25*	*25*	*25*	*25*
Construction time	Years	4	4	4	*4*	*4*	*4*	*4*	*4*	*4*	8	8	8	*8*	*8*	*8*	*8*	*8*	*8*	8	8	8	*8*	*8*	*8*	*8*	*8*	*8*
Interest rate		5%	5%	5%	*5%*	*5%*	*5%*	*5%*	*5%*	*5%*	5%	5%	5%	*5%*	*5%*	*5%*	*5%*	*5%*	*5%*	5%	5%	5%	*5%*	*5%*	*5%*	*5%*	*5%*	*5%*
Decommission share		0,1	0,1	0,1	*0,1*	*0,1*	*0,1*	*0,1*	*0,1*	*0,1*	0,7	0,7	0,7	*0,7*	*0,7*	*0,7*	*0,7*	*0,7*	*0,7*	0,7	0,7	0,7	*0,7*	*0,7*	*0,7*	*0,7*	*0,7*	*0,7*
Discount rate (%)		8%	8%	8%	*8%*	*8%*	*8%*	*8%*	*8%*	*8%*	8%	8%	8%	*8%*	*8%*	*8%*	*8%*	*8%*	*8%*	8%	8%	8%	*8%*	*8%*	*8%*	*8%*	*8%*	*8%*
Total investment Cc	**€/M3d**	**386**	**316**	**276**	*450*	*350*	*293*	*365*	*265*	*209*	**793**	**673**	**270**	*793*	*673*	*555*	*793*	*673*	*270*	**490**	**447**	**339**	*516*	*473*	*813*	*372*	*346*	*339*
Annualised inv. cost	**€/M3d/y**	**33,1**	**27**	**24**	*38,6*	*30*	*25*	*31,3*	*23*	*18*	**74,3**	**63**	**25**	*74,3*	*63*	*52*	*74,3*	*63*	*25*	**45,9**	**42**	**32**	*48,3*	*44*	*76*	*34,8*	*32*	*32*
FOM cost	€/M3d/y	19,64	16,63	14,23	*19,64*	*16,63*	*14,23*	*19,64*	*16,63*	*14,23*	4,76	4,48	4,19	*4,76*	*4,48*	*4,19*	*4,76*	*4,48*	*4,19*	4,69	4,42	3,00	*4,69*	*4,42*	*4,14*	*4,69*	*4,42*	*4,14*
Load. Factor	%	29%	31%	32%	*29%*	*32%*	*32%*	*29%*	*32%*	*32%*	80%	85%	85%	*80%*	*85%*	*85%*	*80%*	*85%*	*85%*	80%	85%	85%	*80%*	*85%*	*85%*	*80%*	*85%*	*85%*
Fixed cost	**€/toe**	**1921**	**1503**	**1248,6**	*2120*	*1555*	*1296,5*	*1855*	*1312*	*1057,0*	**1053**	**847**	**369,9**	*1053*	*847*	*704,2*	*1053*	*847*	*369,9*	**674**	**581**	**435,6**	*706*	*611*	*1007,2*	*526*	*461*	*450,0*
Fuel price	**€/toe**										**20**	**22**	**25**	*20*	*22*	*25*	*20*	*22*	*25*	**20**	**22**	**25**	*20*	*22*	*25*	*20*	*22*	*25*
Carbon content	tCO2/toe																											
Carbon price	**€/tCO2**																											
Fuel efficiency	%	100%	100%	100%	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	45%	47%	50%	*45%*	*47%*	*50%*	*45%*	*47%*	*50%*	31%	36%	37%	*31%*	*36%*	*37%*	*31%*	*36%*	*37%*
Fuel cost incl. Carbo	**€/toe**	**0**	**0**	**0**	*0*	*0*	*0*	*0*	*0*	*0*	**44**	**46**	**50**	*44*	*46*	*50*	*44*	*46*	*50*	**64**	**61**	**67**	*64*	*61*	*67*	*64*	*61*	*67*
VOM cost	€/toe	0,1	0,1	0,1	*0,1*	*0,1*	*0,1*	*0,1*	*0,1*	*0,1*	0,15	0,15	0,15	*0,15*	*0,15*	*0,15*	*0,15*	*0,15*	*0,15*	20	20	20	*20*	*20*	*20*	*20*	*20*	*20*
Variable cost	**€/toe**	**0**	**0**	**0**	*0*	*0*	*0*	*0*	*0*	*0*	**45**	**47**	**50**	*45*	*47*	*50*	*45*	*47*	*50*	**84**	**81**	**87**	*84*	*81*	*87*	*84*	*81*	*87*
Production cost	**€/toe**	**1921**	**1503**	**1249**	*2120*	*1555*	*1297*	*1855*	*1312*	*1057*	**1098**	**893**	**420**	*1098*	*893*	*754*	*1098*	*893*	*420*	**758**	**662**	**523**	*790*	*692*	*1095*	*610*	*542*	*537*
Production cost	€/GJ	46	36	30	*51*	*37*	*31*	*45*	*31*	*25*	26	21	10	*26*	*21*	*18*	*26*	*21*	*10*	18	16	13	*19*	*17*	*26*	*15*	*13*	*13*

HYDROGEN PRODUCTION COSTS (3)

Investment cost		**Reference**			*Unfav. Hypoth.*			*Fav. Hypoth.*		
		2000	2025	2050	*2000*	*2025*	*2050*	*2000*	*2025*	*2050*
Therm. Cycle	€/m3d	**135**	**121,5**	**109,35**	*135*	*121,5*	*109,35*	*135*	*121,5*	*109,35*
Electrolyser	€/m3d	**118**	**105**	**100**	*118*	*105*	*100*	*118*	*105*	*100*

Hydrogen Technologies		**Electrolysis - Grid electricity**			*Electrolysis - Grid elec - Unfav. Hypoth.*			*Electrolysis - Grid elec - Fav. Hypoth.*			**Electrolysis - Wind**			*Electrolysis - Wind - Unfav. Hypoth.*			*Electrolysis - Wind - Fav. Hypoth.*		
€ 2 000		2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050
Floor costs		70			*70*			*70*			100			*100*			*100*		
Overn. Inv. Cost	€/M3d	**118**	**105**	**100**	*118*	*105*	*100*	*118*	*105*	*100*	**251**	**211**	**193**	*289*	*242*	*209*	*239*	*206*	*188*
Overn. Inv. Cost	*€/kW*	*944*	*840*	*800*	*944*	*840*	*800*	*944*	*840*	*800*	*2005*	*1688*	*1542*	*2309*	*1932*	*1674*	*1915*	*1649*	*1501*
Other costs	€/M3d																		
Technical lifetime	Years	25	25	25	*25*	*25*	*25*	*25*	*25*	*25*	25	25	25	*25*	*25*	*25*	*25*	*25*	*25*
Construction time	Years	3	3	3	*3*	*3*	*3*	*3*	*3*	*3*	8	8	8	*8*	*8*	*8*	*8*	*8*	*8*
Interest rate		5%	5%	5%	*5%*	*5%*	*5%*	*5%*	*5%*	*5%*	5%	5%	5%	*5%*	*5%*	*5%*	*5%*	*5%*	*5%*
Decommission share		0,1	0,1	0,1	*0,1*	*0,1*	*0,1*	*0,1*	*0,1*	*0,1*	0,7	0,7	0,7	*0,7*	*0,7*	*0,7*	*0,7*	*0,7*	*0,7*
Discount rate (%)		8%	8%	8%	*8%*	*8%*	*8%*	*8%*	*8%*	*8%*	8%	8%	8%	*8%*	*8%*	*8%*	*8%*	*8%*	*8%*
Total investment Co	**€/M3d**	**131**	**116**	**111**	*131*	*116*	*111*	*131*	*116*	*111*	**340**	**286**	**261**	*391*	*327*	*284*	*324*	*279*	*254*
Annualised inv. cost	**€/M3d/y**	**12,3**	**11**	**10**	*12,3*	*11*	*10*	*12,3*	*11*	*10*	**31,8**	**27**	**24**	*36,6*	*31*	*27*	*30,4*	*26*	*24*
FOM cost	€/M3d/y	1,37	1,10	0,82	*1,37*	*1,10*	*0,82*	*1,37*	*1,10*	*0,82*	4,69	4,42	4,14	*4,69*	*4,42*	*4,14*	*4,69*	*4,42*	*4,14*
Load. Factor	%	40%	40%	40%	*30%*	*30%*	*30%*	*80%*	*80%*	*80%*	28%	28%	28%	*28%*	*28%*	*28%*	*28%*	*28%*	*28%*
Fixed cost	**€/toe**	**363**	**320**	**298,8**	*484*	*427*	*398,4*	*182*	*160*	*149,4*	**1390**	**1188**	**1089,5**	*1574*	*1336*	*1168,9*	*1335*	*1164*	*1064,5*
Fuel price	**€/toe**	**400**	**425**	**450**	400	425	450	400	425	450									
Carbon content	tCO2/toe																		
Carbon price	**€/tCO2**																		
Fuel efficiency	%	75%	75%	75%	*75%*	*75%*	*75%*	*80%*	*80%*	*80%*	100%	100%	100%	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*
Fuel cost incl. Carbo	**€/toe**	**533**	**567**	**600**	*533*	*567*	*600*	*500*	*531*	*563*	**0**	**0**	**0**	*0*	*0*	*0*	*0*	*0*	*0*
VOM cost	€/toe	21,1	21,1	21,1	*21,1*	*21,1*	*21,1*	*21,1*	*21,1*	*21,1*									
Variable cost	**€/toe**	**554**	**588**	**621**	*554*	*588*	*621*	*521*	*552*	*584*	**0**	**0**	**0**	*0*	*0*	*0*	*0*	*0*	*0*
Production cost	**€/toe**	**918**	**908**	**920**	*1039*	*1015*	*1020*	*703*	*712*	*733*	**1390**	**1188**	**1090**	*1574*	*1336*	*1169*	*1335*	*1164*	*1064*
Production cost	€/GJ	22	22	22	*25*	*24*	*24*	*17*	*17*	*18*	33	29	26	*38*	*32*	*28*	*32*	*28*	*26*

CAPTURE AND STORAGE (1)

Differential Cost		Pulverised coal (supercr.). - w. C&S			IGCC - Coal - w. C&S			Gaz turbine - Combined cycle - w. C&S		
99 €		2000	2025	2050	2000	2025	2050	2000	2025	2050
CO2 Capture Inv	€/kW	953	667	428	508	336	192	395	336	214
CO2 Sequestr Inv	€/kW	60	56	54	61	57	55	28	27	25
FOM cost	€/kW/y	7	6	6	10	9	9	4	4	3
Fuel efficiency ratio	%	80%	83%	85%	84%	89%	89%	87%	93%	93%
CCS rate	%	87%	88%	88%	88%	89%	89%	89%	89%	89%
VOM cost	€/ MWh	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5

Differential Cost		Gas steam reforming - w. C&S			Coal partial oxydation w. C&S		
99€ - 95$		2000	2025	2050	2000	2025	2050
CO2 Capture Inv	€/M3d	22	16	17	69	65	53
CO2 Sequestr Inv	€/M3d	5,0	5,0	5,0	5,0	5,0	5,0
FOM cost	€/M3d/y	0,28	0,26	0,25	0,71	0,67	0,63
CCS rate	%	75%	78%	80%	80%	83%	85%
Fuel efficiency	%	84%	87%	90%	70%	79%	85%
VOM cost	toe	18	17	16	50	40	30

Large Scale Power		Pulverised coal (supercr.)			*Charb pulv superC - Unfav. hypoth.*			*Charb pulv superC - Fav. hypoth.*			Pulverised coal (supercr.) - w. C&S		
99 €		2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050
Floor costs		600			900			800			900		
Overn. Inv. Cost	€/kW	1200	1050	900	1300	1150	1000	1000	950	900	2153	1717	1328
Other costs	€/kW												
Technical lifetime	Years	35	35	35	35	35	35	35	35	35	35	35	35
Construction time	Years	3	3	3	3	3	3	3	3	3	4	4	4
Interest rate	%	0	0	0	0	0	0	0	0	0	0	0	0
Decommission share	%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Discount rate (%)	%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%
Total investment Cc	**€/kW**	**1330**	**1164**	**997**	1441	1275	1108	1108	1053	997	**2443**	**1948**	**1507**
Fixed cost	**€/kWy**	**114**	**100**	**86**	124	109	95	95	90	86	**210**	**167**	**129**
FOM cost	€/kWy	40	38	36	45	42	40	40	38	36	47	44	42
Load. Factor	%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%
Fixed cost	**€/MWh**	**21**	**19**	**16**	23	20	18	18	17	16	**34**	**28**	**23**
Invest per input	€/toe												
Fuel price	**€/toe**	**57**	**71**	**100**	57	71	100	57	71	100	**57**	**71**	**100**
Carbon content	tCO2/toe	4	4	4	4	4	4	4	4	4	4	4	4
Carbon price	**€/tCO2**	**0,0**	**0,0**	**0,0**	0,0	0,0	0,0	0,0	0,0	0,0	**0,0**	**0,0**	**0,0**
Fuel efficiency	%	44%	48%	50%	43%	46%	48%	44%	48%	50%	35%	40%	42%
Fuel input	toe/kW	1,5	1,3	1,3	1,5	1,4	1,3	1,5	1,3	1,3	1,8	1,6	1,5
C&C rate	%										0,9	0,9	0,9
CO^2 emitted	CO^2/MWh	0,8	0,7	0,7	0,8	0,7	0,7	0,8	0,7	0,7	0,1	0,1	0,1
Fuel cost incl. Carb	**€/MWh**	**11**	**13**	**17**	11	13	18	11	13	17	**14**	**15**	**20**
VOM cost	**€/MWh**	3	3	3	3	3	3	2	2	2	3	3	3
Variable cost	**€/MWh**	**14**	**15**	**20**	14	16	20	13	15	19	**17**	**18**	**23**
Capt. / sequest cost	€/tCO²										**26**	**22**	**18**
Production cost	**€/MWh**	34	34	36	37	36	39	31	32	36	51	47	46

Large Scale Power		*Pulv. coal w. C&S - Unfav. hypoth.*			*Pulv. coal w.C&S - Fav. hypoth.*			Sequestration			*Sequest. - Unfav. hypoth.*			*Sequest. - Fav. hypoth.*		
99 €		2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050
Floor costs		1000			900			40			70			30		
Overn. Inv. Cost	€/kW	2253	1817	1428	1953	1617	1328	60	56	54	110	102	99	55	51	50
Other costs	€/kW															
Technical lifetime	Years	35	35	35	35	35	35	50	50	50	50	50	50	50	50	50
Construction time	Years	4	4	4	4	4	4	3	3	3	3	3	3	3	3	3
Interest rate	%	0	0	0	0	0	0	5%	5%	5%	5%	5%	5%	5%	5%	5%
Decommission share	%	10%	10%	10%	10%	10%	10%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Discount rate (%)	%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%
Total investment Cc	**€/kW**	2557	2062	1621	2216	1835	1507	**66**	**61**	**59**	121	112	109	61	56	55
Fixed cost	**€/kWy**	219	177	139	190	157	129	**5**	**5**	**5**	10	9	9	5	5	4
FOM cost	€/kWy	52	48	46	47	44	42									
Load. Factor	%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%
Fixed cost	**€/MWh**	36	30	25	32	27	23	**1**	**1**	**1**	1	1	1	1	1	1
Invest per input	€/toe															
Fuel price	**€/toe**	57	71	100	57	71	100									
Carbon content	tCO2/toe	4	4	4	4	4	4	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0
Carbon price	**€/tCO2**	0,0	0,0	0,0	0,0	0,0	0,0	**0**	**0**	**0**	0	0	0	0	0	0
Fuel efficiency	%	34%	38%	41%	35%	40%	42%	35%	40%	42%	34%	38%	41%	35%	40%	42%
Fuel input	toe/kW	1,9	1,7	1,6	1,8	1,6	1,5	1,8	1,6	1,5	1,9	1,7	1,6	1,8	1,6	1,5
C&C rate	%	0,9	0,9	0,9	0,9	0,9	0,9	87,0%	87,7%	87,7%	87,0%	87,7%	87,7%	87,0%	87,7%	87,7%
CO^2 emitted	CO^2/MWh	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
Fuel cost incl. Carb	**€/MWh**	14	16	21	14	15	20									
VOM cost	**€/MWh**	3	3	3	3	3	3									
Variable cost	**€/MWh**	17	19	24	16	18	23									
Capt. / sequest cost	€/tCO²	26	21	17	26	21	17	1,12	1,12	1,12	1,99	1,93	1,96	1,02	1,01	1,02
Production cost	**€/MWh**	54	49	49	48	45	46									

CAPTURE AND STORAGE (2)

Differential Cost 99 €		Pulverised coal (supercr.). - w. C&S			IGCC - Coal - w. C&S			Gaz turbine - Combined cycle - w. C&S		
		2000	2025	2050	2000	2025	2050	2000	2025	2050
CO2 Capture Inv	€/kW	953	667	428	508	336	192	395	336	214
CO2 Sequestr Inv	€/kW	#REF!	#REF!	#REF!	61	57	55	28	27	25
FOM cost	€/kW/y	7	6	6	10	9	9	4	4	3
Fuel efficiency ratio	%	80%	83%	85%	84%	89%	89%	87%	93%	93%
CCS rate	%	87%	88%	88%	88%	89%	89%	89%	89%	89%
VOM cost	€/ MWh	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5

Differential Cost 99€ - 95$		Gas steam reforming - w. C&S			Coal partial oxydation w. C&S		
		2000	2025	2050	2000	2025	2050
CO2 Capture Inv	€/M3d	22	16	17	69	65	53
CO2 Sequestr Inv	€/M3d	5,0	5,0	5,0	5,0	5,0	5,0
FOM cost	€/M3d/y	0,28	0,26	0,25	0,71	0,67	0,63
CCS rate	%	75%	78%	80%	80%	83%	85%
Fuel efficiency	%	84%	87%	90%	70%	79%	85%
VOM cost	toe	18	17	16	50	40	30

Large Scale Power 99 €		IGCC - Coal			IGCC - Coal - Unfav. hypoth.			IGCC - Coal - Fav. hypoth.			IGCC - Coal - w. C&S		
		2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050
Floor costs			900			900			700			1000	
Overn. Inv. Cost	€/kW	1500	1350	1200	1600	1400	1300	1300	1100	1000	2008	1686	1392
Other costs	€/kW												
Technical lifetime	Years	35	35	35	35	35	35	35	35	35	35	35	35
Construction time	Years	3	3	3	3	3	3	3	3	3	4	4	4
Interest rate	%	0	0	0	0	0	0	0	0	0	0	0	0
Decommission share	%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Discount rate (%)	%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%
Total investment Cc	**€/kW**	**1657**	**1492**	**1326**	1768	1547	1436	1436	1215	1105	**2272**	**1908**	**1575**
Fixed cost	**€/kWy**	**142**	**128**	**114**	152	133	123	123	104	95	**195**	**164**	**135**
FOM cost	€/kWy	45	41	36	48	42	39	39	33	30	55	49	45
Load. Factor	%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%
Fixed cost	**€/MWh**	**25**	**23**	**20**	27	23	22	22	18	17	**34**	**29**	**24**
Fuel price	**€/toe**	**57**	**71**	**100**	57	71	100	57	71	100	**57**	**71**	**100**
Carbon content	tCO2/toe	4	4	4	4	4	4	4	4	4	4	4	4
Carbon price	**€/tCO2**	**0,0**	**0,0**	**0,0**	0,0	0,0	0,0	0,0	0,0	0,0	**0,0**	**0,0**	**0,0**
Fuel efficiency	%	45%	49%	51%	43%	45%	47%	46%	49%	51%	38%	43%	45%
Fuel input	toe/kW	1,4	1,3	1,3	1,5	1,4	1,4	1,4	1,3	1,3	1,7	1,5	1,4
C&C rate	%										0,9	0,9	0,9
CO² emitted	t/MWh	0,76	0,70	0,67	0,80	0,76	0,73	0,75	0,70	0,67	0,11	0,08	0,08
Fuel cost incl. Carb	**€/MWh**	**11**	**13**	**17**	11	14	18	11	13	17	**13**	**14**	**19**
VOM cost	€/MWh	5	4	3	6	6	5	4	4	3	6	5	4
Variable cost	**€/MWh**	**16**	**17**	**20**	17	19	23	15	16	20	**18**	**19**	**23**
Capt. / sequest cost	€/tCO²										**17**	**13**	**11**
Production cost	**€/MWh**	41	39	40	44	43	45	36	34	37	52	47	47

Large Scale Power 99 €		IGCC - Coal w. C&S - Unfav. hypoth.			IGCC - Coal w. C&S - Fav. hypoth.			Sequestration			Sequest. - Unfav. hypoth.			Sequest. - Fav. hypoth.		
		2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050
Floor costs			1100			800			40			70			30	
Overn. Inv. Cost	€/kW	2108	1736	1492	1808	1436	1192	61	57	55	110	104	100	55	52	50
Other costs	€/kW															
Technical lifetime	Years	35	35	35	35	35	35	50	50	50	50	50	50	50	50	50
Construction time	Years	4	4	4	4	4	4	3	3	3	3	3	3	3	3	3
Interest rate	%	0	0	0	0	0	0	5%	5%	5%	5%	5%	5%	5%	5%	5%
Decommission share	%	5%	5%	5%	5%	5%	5%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Discount rate (%)	%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%
Total investment Cc	**€/kW**	2385	1965	1689	2046	1625	1349	**67**	**63**	**61**	121	114	110	61	57	55
Fixed cost	**€/kWy**	205	169	145	176	139	116	**5**	**5**	**5**	10	9	9	5	5	5
FOM cost	€/kWy	58	51	48	49	42	39									
Load. Factor	%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%
Fixed cost	**€/MWh**	35	29	26	30	24	21	**1**	**1**	**1**	1	1	1	1	1	1
Fuel price	**€/toe**	57	71	100	57	71	100									
Carbon content	tCO2/toe	4	4	4	4	4	4	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0
Carbon price	**€/tCO2**	0,0	0,0	0,0	0,0	0,0	0,0	**0**	**0**	**0**	0	0	0	0	0	0
Fuel efficiency	%	36%	40%	42%	39%	43%	45%	38%	43%	45%	36%	40%	42%	39%	43%	45%
Fuel input	toe/kW	1,8	1,6	1,5	1,7	1,5	1,4	1,7	1,5	1,4	1,8	1,6	1,5	1,7	1,5	1,4
C&C rate	%	0,9	0,9	0,9	0,9	0,9	0,9	87,8%	89,2%	89,2%	87,8%	89,2%	89,2%	87,8%	89,2%	89,2%
CO² emitted	t/MWh	0,12	0,09	0,09	0,11	0,09	0,08	0,11	0,08	0,08	0,12	0,09	0,09	0,11	0,09	0,08
Fuel cost incl. Carb	**€/MWh**	14	15	21	13	14	19									
VOM cost	€/MWh	7	6	6	5	4	4									
Variable cost	**€/MWh**	20	21	26	17	18	23									
Capt. / sequest cost	€/tCO²	16	12	11	17	13	11	1,12	1,12	1,12	1,95	1,87	1,88	1,04	1,02	1,02
Production cost	**€/MWh**	55	51	52	47	42	43									

CAPTURE AND STORAGE (3)

Differential Cost		Pulverised coal (supercr.). - w. C&S			IGCC - Coal - w. C&S			Gaz turbine - Combined cycle - w. C&S		
99 €		2000	2025	2050	2000	2025	2050	2000	2025	2050
CO2 Capture Inv	€/kW	953	667	428	508	336	192	395	336	214
CO2 Sequestr Inv	€/kW	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	28	27	25
FOM cost	€/kW/y	7	6	6	10	9	9	4	4	3
Fuel efficiency ratio	%	80%	83%	85%	84%	89%	89%	87%	93%	93%
CCS rate	%	87%	88%	88%	88%	89%	89%	89%	89%	89%
VOM cost	€/ MWh	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5

Differential Cost		Gas steam reforming - w. C&S			Coal partial oxydation w. C&S		
99€ - 95$		2000	2025	2050	2000	2025	2050
CO2 Capture Inv	€/M3d	22	16	17	69	65	53
CO2 Sequestr Inv	€/M3d	5,0	5,0	5,0	5,0	5,0	5,0
FOM cost	€/M3d/y	0,28	0,26	0,25	0,71	0,67	0,63
CCS rate	%	75%	78%	80%	80%	83%	85%
Fuel efficiency	%	84%	87%	90%	70%	79%	85%
VOM cost	toe	18	17	16	50	40	30

Large Scale Power		Gaz turbine - Combined cycle			GTCC - Unfav. hypoth.			GTCC - Fav. hypoth.			Gaz turbine - Combined cycle - w. C&S			GTCC C&S - Unfav. hypoth.			GTCC C&S - Fav. hypoth.			Sequestration			Sequest. - Unfav. hypoth.			Sequest. - Fav. hypoth.		
99 €		2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050
Floor costs		300			400			300			400			500			400			10			30			10		
Overn. Inv. Cost	€/kW	450	425	400	550	525	500	400	375	350	845	761	614	945	861	714	795	711	564	28	27	25	51	48	46	25	24	22
Other costs	€/kW																											
Technical lifetime	Years	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	25	50	50	50	50	50	50	50	50	50
Construction time	Years	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	3	3	3	3	3	3	3	3	3
Interest rate	%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5%	5%	5%	5%	5%	5%	5%	5%	5%
Decommission share	%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Discount rate (%)	%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%
Total investment Cc	**€/kW**	493	466	438	603	575	548	438	411	384	949	854	689	1061	967	801	893	798	633	31	30	28	56	53	50	28	26	25
Fixed cost	**€/kWy**	46	44	41	56	54	51	41	38	36	89	80	65	99	91	75	84	75	59	3	2	2	5	4	4	2	2	2
FOM cost	€/kWy	18	17	16	22	21	20	16	15	14	22	21	19	26	25	23	20	19	17									
Load. Factor	%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	85%	85%	85%	85%	85%	85%	85%	85%	85%
Fixed cost	**€/MWh**	8	8	7	10	10	9	7	7	6	14	13	11	16	15	12	13	12	10	0	0	0	1	1	1	0	0	0
Fuel price	**€/toe**	120	200	360	120	200	360	120	200	360	120	200	360	120	200	360	120	200	360									
Carbon content	tCO2/toe	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2
Carbon price	**€/tCO2**	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0	0	0	0	0	0	0	0	0
Fuel efficiency	%	55%	59%	62%	54%	57%	60%	55%	59%	62%	48%	54%	57%	47%	53%	56%	48%	54%	57%	48%	54%	57%	47%	53%	56%	48%	54%	57%
Fuel input	toe/kW	1,2	1,2	1,1	1,3	1,2	1,1	1,2	1,2	1,1	1,4	1,3	1,2	1,5	1,3	1,2	1,4	1,3	1,2	1,3	1,2	1,1	1,4	1,2	1,2	1,3	1,2	1,1
C&C rate	%										0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	0,9	89,0%	89,0%	89,0%	89,0%	89,0%	89,0%	89,0%	89,0%	89,0%
CO^{2} emitted	t/MWh	0,35	0,33	0,31	0,36	0,34	0,32	0,35	0,33	0,31	0,04	0,04	0,04	0,05	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,04	0,05	0,04	0,04	0,04	0,04	0,04
Fuel cost incl. Carb	**€/MWh**	19	29	50	19	30	52	19	29	50	22	32	54	22	33	56	22	32	54									
VOM cost	€/MWh	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2									
Variable cost	**€/MWh**	20	31	52	21	32	53	20	31	51	24	34	56	24	34	58	23	33	55									
Capt. / sequest cost	€/tCO^{2}										31	28	29	29	26	27	29	26	27	1,12	1,12	1,12	1,98	1,96	1,95	0,99	0,99	0,99
Production cost	**€/MWh**	29	39	59	31	41	62	28	38	58	38	47	67	40	49	70	36	45	65									

CAPTURE AND STORAGE (4)

Differential Cost 99 €		**Pulverised coal (supercr.). - w. C&S** 2000	2025	2050	**IGCC - Coal - w. C&S** 2000	2025	2050	**Gaz turbine - Combined cycle - w. C&S** 2000	2025	2050
CO2 Capture Inv	€/kW	953	667	428	508	336	192	395	336	214
CO2 Sequestr Inv	€/kW	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!
FOM cost	€/kW/y	7	6	6	10	9	9	4	4	3
Fuel efficiency ratio	%	80%	83%	85%	84%	89%	89%	87%	93%	93%
CCS rate	%	87%	88%	88%	88%	89%	89%	89%	89%	89%
VOM cost	€/ MWh	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5

Differential Cost 99€ - 95$		**Gas steam reforming - w. C&S** 2000	2025	2050	**Coal partial oxydation w. C&S** 2000	2025	2050
CO2 Capture Inv	€/M3d	22	16	17	69	65	53
CO2 Sequestr Inv	€/M3d	5,0	5,0	5,0	5,0	5,0	5,0
FOM cost	€/M3d/y	0,28	0,26	0,25	0,71	0,67	0,63
CCS rate	%	75%	78%	80%	80%	83%	85%
Fuel efficiency	%	84%	87%	90%	70%	79%	85%
VOM cost	toe	18	17	16	50	40	30

Hydrogen Technologies **€ 2 000**		**Coal partial oxydation** 2000	2025	2050	*Coal partial oxydation - Unfav. hypoth.* 2000	2025	2050	*Coal partial oxydation - Fav. hypoth.* 2000	2025	2050	**Coal partial oxydation - w. C&S** 2000	2025	2050
Floor costs		30			40			30			50		
Overn. Inv. Cost	€/m3d	107	96	65	150	143	97	107	96	65	176	161	118
Overn. Inv. Cost	*€/kW*	856	768	520	1200	1143	774	856	768	520	1408	1288	944
Other costs	€/m3d												
Technical lifetime	Years	35	35	35	35	35	35	35	35	35	35	35	35
Construction time	Years	3	3	3	3	3	3	3	3	3	4	4	4
Interest rate	%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Decommission share	%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Discount rate (%)	%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%
Total investment Cc	**€/m3d**	118	106	72	166	158	107	118	106	72	199	182	134
Annualised inv. cos	**€/m3d/yr**	10	9	6	14	14	9	10	9	6	17	16	11
FOM cost	€/m3d/yr	0,97	0,78	0,58	0,97	0,78	0,58	0,97	0,78	0,58	1,68	1,45	1,21
Load. Factor	%	90%	90%	90%	90%	90%	90%	90%	90%	90%	80%	83%	85%
Fixed cost	**€/toe**	132	117	80	180	170	115	132	117	80	250	219	159
Fuel price	**€/toe**	57	71	100	57	71	100	57	71	100	57	71	100
Carbon content	tCO2/toe	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0
Carbon price	**€/tCO2**	0	0	0	0	0	0	0	0	0	0	0	0
Fuel efficiency	%	59%	63%	65%	28%	35%	40%	28%	37%	47%	41%	50%	56%
C&C rate	%										0,8	0,8	0,9
CO² emitted	tCO²/toe	6,7	6,3	6,1	14,1	11,3	9,9	14,1	10,6	8,4	1,9	1,4	1,1
Fuel cost incl. Carb	**€/toe**	97	113	154	204	204	250	204	191	213	138	144	180
Fuel cost w/o Carbon		97	113	154	204	204	250	204	191	213	138	144	180
VOM cost	€/toe	35	35	35	35	35	35	35	35	35	85	75	65
Variable cost	**€/toe**	132	148	189	239	239	285	239	226	248	223	219	245
Capt. / sequest cost	€/tCO²										44	35	27
Production cost	**€/toe**	264	265	269	419	409	400	371	343	328	473	438	404
Production cost	€/GJ	6	6	6	10	10	10	9	8	8	11	11	10

Hydrogen Technologies **€ 2 000**		*Coal partial oxydation - C&S - Unfav. hypoth.* 2000	2025	2050	*Coal partial oxydation - C&S - Fav. hypoth.* 2000	2025	2050	**Sequestration** 2000	2025	2050	*Sequest. - Unfav. hypoth.* 2000	2025	2050	*Sequest. - Fav. hypoth.* 2000	2025	2050
Floor costs		70			50			3			3			3		
Overn. Inv. Cost	€/m3d	219	208	150	176	161	118	5	5	5	5	5	5	5	5	5
Overn. Inv. Cost	*€/kW*	1752	1663	1198	1408	1288	944	38	39	40	38	39	40	38	39	40
Other costs	€/m3d															
Technical lifetime	Years	35	35	35	35	35	35	50	50	50	50	50	50	50	50	50
Construction time	Years	4	4	4	4	4	4	3	3	3	3	3	3	3	3	3
Interest rate	%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Decommission share	%	5%	5%	5%	5%	5%	5%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Discount rate (%)	%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%
Total investment Cc	**€/m3d**	248	235	169	199	182	134	5	5	6	5	5	6	5	5	6
Annualised inv. cos	**€/m3d/yr**	21	20	15	17	16	11	0	0	0	0	0	0	0	0	0
FOM cost	€/m3d/yr	1,68	1,45	1,21	1,68	1,45	1,21									
Load. Factor	%	80%	83%	85%	80%	83%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%
Fixed cost	**€/toe**	306	278	197	250	219	159	5	6	6	5	6	6	5	6	6
Fuel price	**€/toe**	57	71	100	57	71	100									
Carbon content	tCO2/toe	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0	4,0
Carbon price	**€/tCO2**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fuel efficiency	%	20%	28%	34%	20%	29%	40%	41%	50%	56%	20%	28%	34%	20%	29%	40%
C&C rate	%	0,8	0,8	0,9	0,8	0,8	0,9	80%	83%	85%	80%	83%	85%	80%	83%	85%
CO² emitted	tCO²/toe	4,0	2,4	1,7	4,0	2,3	1,5	1,918	1,355	1,069	4,041	2,438	1,738	4,041	2,285	1,479
Fuel cost incl. Carb	**€/toe**	292	259	293	292	242	249									
Fuel cost w/o Carbon		292	259	293	292	242	249									
VOM cost	€/toe	85	75	65	85	75	65									
Variable cost	**€/toe**	377	334	358	377	317	314									
Capt. / sequest cost	€/tCO²	26	23	19	25	23	21	1,12	1,12	1,12	0,53	0,62	0,69	0,53	0,67	0,81
Production cost	**€/toe**	682	612	555	627	537	473									
Production cost	€/GJ	16	15	13	15	13	11									

CAPTURE AND STORAGE (5)

Differential Cost		Pulverised coal (supercr.). - w. C&S			IGCC - Coal - w. C&S			Gaz turbine - Combined cycle - w. C&S		
99 €		2000	2025	2050	2000	2025	2050	2000	2025	2050
CO2 Capture Inv	€/kW	953	667	428	508	336	192	395	336	214
CO2 Sequestr Inv	€/kW	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!	#REF!
FOM cost	€/kW/y	7	6	6	10	9	9	4	4	3
Fuel efficiency ratio	%	80%	83%	85%	84%	89%	89%	87%	93%	93%
CCS rate	%	87%	88%	88%	88%	89%	89%	89%	89%	89%
VOM cost	€/ MWh	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5	0,5

Differential Cost		Gas steam reforming - w. C&S			Coal partial oxydation w. C&S		
99€ - 95$		2000	2025	2050	2000	2025	2050
CO2 Capture Inv	€/M3d	22	16	17	69	65	53
CO2 Sequestr Inv	€/M3d	5,0	5,0	5,0	5,0	5,0	5,0
FOM cost	€/M3d/y	0,28	0,26	0,25	0,71	0,67	0,63
CCS rate	%	75%	78%	80%	80%	83%	85%
Fuel efficiency	%	84%	87%	90%	70%	79%	85%
VOM cost	toe	18	17	16	50	40	30

Hydrogen Technologies		Gas steam reforming			*Gas steam reforming - Hyp. Défav.*			*Gas steam reforming - Fav. hypoth.*			Gas steam reforming - w. C&S			*Gas steam reforming - C&S - Unfav. hypoth.*			*Gas steam reforming - C&S - Fav. hypoth.*			Sequestration			*Sequest. - Unfav. hypoth.*			*Sequest. - Fav. hypoth.*		
€ 2 000		2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050	2000	2025	2050
Floor costs		30			40			30			40			40			40			1			1			1		
Overn. Inv. Cost	€/m3d	42	40	38	60	50	45	42	40	38	64	56	55	82	66	62	64	56	55	2	2	2	2	2	2	2	2	2
Overn. Inv. Cost	*€/kW*	336	320	304	480	400	360	336	320	304	512	448	440	656	528	496	512	448	440	17	17	17	17	17	17	17	17	17
Other costs	€/m3d																											
Technical lifetime	Years	25	25	25	25	25	25	25	25	25	35	35	35	35	35	35	35	35	35	50	50	50	50	50	50	50	50	50
Construction time	Years	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	3	3	3	3	3	3	3	3	3
Interest rate	%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%
Decommission share	%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	5%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Discount rate (%)	%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%
Total investment Cc	**€/m3d**	**47**	**44**	**42**	67	55	50	47	44	42	**72**	**63**	**62**	93	75	70	72	63	62	**2**	**2**	**2**	2	2	2	2	2	2
Annualised inv. cost	**€/m3d/yr**	**4**	**4**	**4**	6	5	5	4	4	4	**6**	**5**	**5**	8	6	6	6	5	5	**0**	**0**	**0**	0	0	0	0	0	0
FOM cost	€/m3d/yr	0,26	0,25	0,24	0,50	0,45	0,42	0,26	0,25	0,24	0,54	0,51	0,49	0,78	0,71	0,67	0,54	0,51	0,49									
Load. Factor	%	90%	90%	90%	90%	90%	90%	90%	90%	90%	80%	83%	85%	80%	83%	85%	80%	83%	85%	85%	85%	85%	85%	85%	85%	85%	85%	85%
Fixed cost	**€/toe**	**55**	**52**	**50**	80	67	60	55	52	50	**90**	**76**	**73**	116	91	84	90	76	73	**2**	**2**	**2**	2	2	2	2	2	2
Fuel price	**€/toe**	**120**	**200**	**360**	120	200	360	120	200	360	**120**	**200**	**360**	120	200	360	120	200	360									
Carbon content	tCO2/toe	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2	2,2
Carbon price	**€/tCO2**	**0**	**0**	**0**	0	0	0	0	0	0	**0**	**0**	**0**	0	0	0	0	0	0	**0**	**0**	**0**	0	0	0	0	0	0
Fuel efficiency	%	74%	78%	81%	72%	74%	77%	74%	78%	81%	62%	68%	73%	60%	65%	69%	62%	68%	73%	62%	68%	73%	60%	65%	69%	62%	68%	73%
C&C rate	%										0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	0,8	75%	78%	80%	75%	78%	80%	75%	78%	80%
CO² emitted	tCO²/toe	3,023	2,868	2,761	3,106	3,023	2,905	3,023	2,868	2,761	0,900	0,724	0,613	0,925	0,763	0,645	0,900	0,724	0,613	0,900	0,724	0,613	0,925	0,763	0,645	0,900	0,724	0,613
Fuel cost incl. Carbo	**€/toe**	**162**	**256**	**444**	167	270	468	162	256	444	**193**	**294**	**493**	198	310	519	193	294	493									
Fuel cost w/o Carbon		**162**	**256**	**444**	167	270	468	162	256	444	**193**	**294**	**493**	198	310	519	193	294	493									
VOM cost	€/toe	6	6	6	20	20	20	6	6	6	24	22,9796	22	38	36,9796	36	24	22,9796	22									
Variable cost	**€/toe**	**168**	**262**	**450**	187	290	488	168	262	450	**217**	**317**	**515**	236	347	555	217	317	515									
Capt. / sequest cost	€/tCO²										40	37	41	40	36	40	40	37	41	1,12	1,11	1,10	1,09	1,05	1,05	1,12	1,11	1,10
Production cost	**€/toe**	**223**	**315**	**500**	266	357	548	223	315	500	**307**	**394**	**588**	353	439	639	307	394	588									
Production cost	€/GJ	5	8	12	6	9	13	5	8	12	7	9	14	8	11	15	7	9	14									

III. Modelling Technology Dynamics Basic Tools

N. Kouvaritakis and V. Panos (1) ICCS-NTUA

1. Two Factor Learning Curves Specification and Estimation

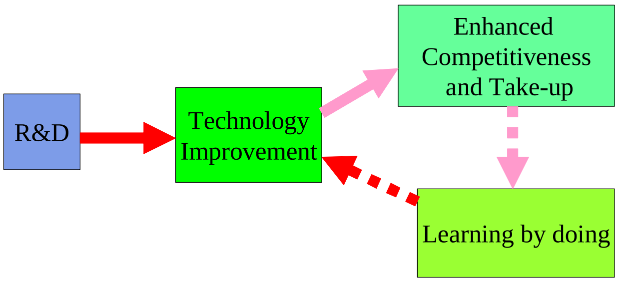
1.1. Introduction

The unique information database presented in Part B of the SAPIENTIA Final Report has not only served as a suitable sample for estimation and a starting point for model runs, but also represents the state of the art of the SAPIENTIA database for the study and econometric estimate of the Two Factor Learning Curves for some key new energy technologies. The specification and estimation of the two factor learning curve relations for use in the large models as well as in PROMETHEUS is the backbone for meaningful policy analysis in the context of the SAPIENTIA project as they constitute the main vehicle and first step through which R&D actions translate into impacts. Their estimation provides essential input for the stochastic model (PROMETHEUS) in the form of variance and co-variance of learning by research and learning by doing effects.

Traditional technology dynamics has long recognised the importance of learning by experience in determining the cost and technical performance of technologies. Under this scheme, these improvements occur presumably without cost except perhaps those incurred in demonstration. However, it is also widely accepted that R&D can contribute directly to technological improving. Furthermore, in order to address the main questions posed in the SAPIENTIA project concerning the efficacy of R&D, it is clear that R&D must figure explicitly in the technology dynamics specification. For this reason, a two factor learning mechanism has been adopted recognising learning attributed to research effort (learning-by-research) and learning arising from the experience gained through technology uptake (learning-by-doing). Variants of this learning mechanism have been introduced in all models.

The general scheme of the technology dynamics mechanism is presented below:

Figure 1-1: General scheme of the technology dynamics mechanism



Under this scheme, an R&D action leads directly to technological improvement, which in turn enhances competitiveness of a particular option and leads to increased technology take-up. This latter increase sets in motion learning by experience, which results in further technological improvement, further up-take etc. In this sense, learning by doing acts as an accelerator of the impact of initial R&D effects. Clearly, the cycle contains dampening effects that result in finite overall impacts. This dampening notwithstanding, the inclusion of such mechanisms in models does tend to introduce elements of instability, in particular “lock-in” effects –massive R&D funding on some options may lockout other options that fail to benefit from the learning by experience they could have enjoyed, had such initial R&D infusion not taken place. Models thus become sensitive to initial conditions. On the other hand there is sufficient evidence that this is indeed an accurate representation of the way technical progress has occurred in the past.

Some specific properties have been sought for the specification and estimation of the two factor learning curve formulation: it should incorporate both learning-by-doing and learning-by-research (which is crucial in order to be able to perform the R&D policy exercises), endogenise as much of the technical progress as possible, constrain to technical possibilities as they emerge from perspective analysis, include "Clustering" as fully as available information allows, take carefully into account initial conditions regarding cumulative R&D and equipment stock and capture as much of the above with as few parameters as possible.

1.2. The General Algebraic Specification of a TFLC Equation

Let i be a technology, and c be a cluster. Let us then define $C_{i,t}$ as the capital cost the technology i in time t, $K_{i,t}$ as the installed capacity of technology i in time t, and $R_{i,t}$ the cumulative R&D (both Government Energy R&D and Business Energy R&D) spent on technology i at time t. Then the general formulation of the TFLC equation as estimated for the SAPIENTIA project is:

$$C_{i,t} = C_{i,t-1} \cdot \prod_{c=1}^{l} \left(\frac{cl_{c,t}}{cl_{c,t-1}} \right)^{r_{i,c} \cdot a_{i,t} \cdot cllm_c} \cdot \left(\frac{K_{i,t-1}}{K_{i,t-2}} \right)^{\left(1 - \sum_{c=1}^{l} r_{i,c}\right) \cdot a_{i,t} \cdot caplm_{i,t}} \cdot \left(\frac{R_{i,t-1}}{R_{i,t-2}} \right)^{b_{i,t} \cdot rdlm_{i,t}} \quad (1)$$

Where:

$$cl_{c,t} = \sum_{i=1}^{n} w_{i,c} \cdot K_{i,t-1} \quad (2)$$

$$cllm_c = \begin{cases} 0, \sum_{i=1}^{n} w_{i,c} \cdot K_{i,t-1} \leq \sum_{i=1}^{n} w_{i,c} \cdot caplmt_i \\ 1, otherwise \end{cases} \quad (3)$$

$$a_{i,t} = capelfac_i \cdot e^{s_i \cdot y_{i,t}} \cdot d_{i,t} \quad (4)$$

$$b_{i,t} = rdelfac_i \cdot e^{s_i \cdot y_{i,t}} \cdot d_{i,t} \quad (5)$$

$$y_{i,t} = \frac{-\,floor_i}{\left| floor_i - C_{i,t-1} \right| + 1} \quad (6)$$

Equation (6) calculates the variable $y_{i,t}$, which represents the "distance" of the capital cost of the technology *i* in time *t-1* from the corresponding floor cost $floor_i$ (a notional absolute minimum representing a limit to possible improvement). The $y_{i,t}$ is used in equations (4) and (5), which implement a mechanism for reducing the estimated learning by doing parameter $capelfac_i$ and the corresponding learning by research parameter $rdelfac_i$ as the capital cost approaches asymptotically the floor cost. In order to ensure that the learning process will stop in those cases in which the capital cost is lower than the floor cost, a binary variable $d_{i,t}$ is introduced in the equations (4) and (5):

$$d_{i,t} = \begin{Bmatrix} 0, & C_{i,t-1} < floor_i \\ 1, & C_{i,t-1} \geq floor_i \end{Bmatrix} \quad (7)$$

Moreover, in equations (4) and (5) there is a saturation rate coefficient s_i, regulating the speed at which saturation is reached.

Thus, the final learning parameters, used in the general form of the TFLC equation (1), are calculated in the equations (4) and (5) and they are declining over time as the learning process advances.

In addition, in some cases, it has been assumed that the learning parameters are not effective below a threshold either on capacity or on cumulative R&D. This assumption is necessary especially for new technologies in order to avoid learning when only demonstration versions of these technologies exist, mainly in the first years of the forecast, in order to avoid instability in learning arising from an excessive reliance on initial conditions (data and forecasts). Two binary variables have been introduced to model this, $caplm_i$ and $rdlm_i$, which are defined as follows:

$$caplm_{i,t} = \begin{Bmatrix} 0, & K_{i,t-1} \leq caplmt_i \\ 1, & K_{i,t-1} > caplmt_i \end{Bmatrix} \quad (8)$$

$$rdlm_{i,t} = \begin{Bmatrix} 0, & R_{i,t-1} \leq rdlmt_i \\ 1, & R_{i,t-1} > rdlmt_i \end{Bmatrix} \quad (9)$$

where $caplmt_i$ and $rdlmt_i$ are the capacity and cumulative R&D limits imposed on learning of the technology *i*.

Each technology *i* has a weight $w_{i,c}$ in each cluster *c*, reflecting the importance of the generic technology defining the cluster *c* on the cost structure of technology *i*. Moreover, there is a weight $r_{i,c}$ reflecting the importance of the component belonging to cluster *c* for each technology *i* adjusted for the learning rate of the cluster. The matrices containing the weights are **W** and **R** respectively.

1.3. Technology Classification for the TFLCs

Although effort has been devoted to standardise the specification as much as possible, some exceptions were deemed necessary due to specifities of the technologies. As a result, the technologies are classified into five categories:

- The Cluster Matrix Technologies, for which a cluster matrix is supplied and the general algebraic formulation can be applied
- The Stand Alone Technologies, which are orthogonal technologies and do not need to consider clustering.
- The Perfect Clustering Technologies, the technical and economic characteristics of which are directly related to the corresponding characteristics of other technologies (for example the wind offshore and wind onshore technologies). For these technologies the TFLC equation is applied only for the additional cost.
- The on-board storage technologies, (a sub-category of the perfect clustering technologies) that are shared by different types of vehicles and are only specified in terms of cost.
- The Fuel Cell technologies.

1.3.1. The Cluster Matrix Technologies

This group consists of 19 technologies, mostly for power generation (Table 1-1)

Table 1-1: The cluster matrix technologies

Technology Description	Technology Short Name
Large Hydro	**hyd**
Nuclear (2nd and 3d gen.)	**nuc**
New Nuclear (4th gen.)	**nnd**
Lignite Conventional Thermal	**lct**
Coal Conventional Thermal	**cct**
Supercritical Pulverised Coal	**pfc**
Integrated Coal Gasification	**icg**
Oil Conventional Thermal	**oct**
Oil fired Open Cycle Gas Turbine	**ogc**
Gas Conventional Thermal	**gct**
Gas Turbine Open Cycle	**ggt**
Gas Turbine Combined Cycle	**ggc**
Cogeneration from gas	**chp**
Small Hydro (<25MW)	**shy**
Solar Thermal Power Plant Cylindro-Parabolic	**spp**
Building Integrated PV	**dpv**
Biomass Thermal	**bf2**
Biomass Gasification plus Combined Cycle	**bgt**
Hydrogen from Coal Partial Oxidation	**cpo**
Hydrogen from Biomass Pyrolysis	**bpy**

The initial cluster matrix, as provided by ECN, included more technologies than the ones considered in the estimation, which, for the purpose of the estimation, have been moved to other technology groups.

The technology's components that are shared in the modified cluster matrix have been increased by one component, the "biomass processing", in order to take into account technical characteristics common to all technologies using biomass.

Table 1-2 summarises the components retained and the weight of each component attributed to the total cost of the technology.

Table 1-2: The cluster matrix W used in the estimation of the TFLCs (following MARKAL)

	steam turbine	gas turbine	boiler	recovery CC boiler	gasifier	hydro turbine	nuclear reactor	wind turbine	Biomass processing
HYD						1.00			
NUC	1.00						1.00		
NND	1.00						1.00		
LCT	1.00		1.00						
CCT	1.00		1.00						
PFC	1.00		1.00						
ICG	0.40	0.60		0.40	1.00				
OCT	1.00		1.00						
OGC		1.00							
GCT	1.00		1.00						
GGT		1.00							
GGC	0.33	0.67		0.33					
CHP	0.40	1.00							
SHY						1.00			
SPP	1.00								
BF2	1.00		1.00						1.00
BGT	0.40	0.60		0.40	1.00				1.00
CPO	0.04				1.00				
BPY					0.50				0.50

1.3.2. The Stand - Alone Technologies

This group consists of the following orthogonal technologies:

Table 1-3: The Stand-Alone Technologies

Technology Description	**Technology Short Name**
Building Integrated PV	**dpv**
Wind Turbines Onshore	**wnd**
Conventional Internal Combustion Engine Passenger Car	**conv**
Hydrogen from Gas Steam Reforming (large scale)	**gsr**
Hydrogen from Water Electrolysis (baseload electricity from Grid)	**weg**
CO2 sequestration	**co2seq**
Post-Combustion CO2 capture (Supercritical Pulverised Coal)	**pssc**
Pre-Combustion CO2 capture (Integrated Gasification Combined Cycle)	**cgsc**
Post-Combustion CO2 capture (Gas Turbine Combined Cycle)	**ggsc**
Pre-Combustion CO2 capture (Gas Steam Reforming)	**gssc**
Pre-Combustion CO2 capture (Coal Partial Oxidation)	**cpsc**

It should be noted that although clustering exists between the decentralised building photovoltaics (DPV) and the rural photovoltaic installations (RPV), the latter were not considered in the TFLC estimation because of its poor prospects, so the DPV technology is treated as a stand-alone technology.

1.3.3. The Perfect Clustering Technologies

The technologies participating in this group are:

Table 1-4: The Perfect Clustering Technologies

Technology Description	**Technology Short Name**
Wind Turbines Offshore	**wno**
Electric Passenger Car	**elev**
Hydrogen Internal Combustion Engine Passenger Car	**thyv**
Hybrid Passenger Car	**hybv**
Hydrogen from Solar High-temperature Thermochemical cycles	**sht**
Hydrogen from Nuclear High-temperature Thermochemical cycles	**nht**

The above technologies depend on technologies belonging to the previous two groups. The dependencies are defined as follows:

- WNO: The WNO technology is perfectly clustered with the WND technology. This means that the costs of the WNO are the costs of the WND plus additional costs.
- ELEV: For the engine cost of ELEV clustering with the HYBV car is assumed, in which the weight attributed to the hybrid car is 0.25. Moreover, the electric car efficiency is treated in conjunction with the conventional car efficiency reflecting the fact that improvements in conventional car efficiency related to improvements on the car body also benefit electric cars.
- HYBV: The engine of the hybrid car comprises parts from the engines of the conventional and electric car. The cost reductions of these parts are passed directly to the hybrid with a factor of 0.25 for both electric and conventional engines. There is also a remaining cost, which reflects the complexity of the hybrid car engine and it is therefore specific to the hybrid. The learning equation for the hybrid engine cost, considers only the hybrid-specific cost. Finally as in the case of the efficiency of ELEV car, the hybrid efficiency is treated in conjunction with the conventional efficiency
- SHT: There is perfect clustering between SHT and SPP in the capital costs. The weight attributed to SPP is 0.6, thus the TFLC equation considers only the additional cost of SHT.

- NHT: There is a perfect clustering between NHT and NUC regarding the capital costs, in which the weight attributed to NUC is 0.6. The TFLC equation applies only for the additional capital cost. On the other hand, no learning equation has been estimated for the fixed O&M cost of this technology, since this cost has been assume to be the 60% of the NUC fixed O&M.

Finally, there is also the Hydrogen from Water Electrolysis with dedicated Nuclear Plant (WEN) technology, which is perfectly clustered with nuclear (NUC) and Hydrogen from Water Electrolysis using base-load electricity from grid (WEG) technologies. The capital cost, fixed O&M cost and variable O&M cost of this technology are direct sums of the technical and economic characteristics of NUC and WEG. In addition, its efficiency is the product of the efficiencies of NUC and WEG. As a result, there is no TFLC for any of the technical and economic characteristics of WEN, so this technology is not reported on Table 1-4.

1.3.4. The On-board storage technologies

In this group, the following technologies included:

Table 1-5: The on-board storage technologies

Technology Description	Technology Short Name
Electric Passenger Car on-board storage	**elevst**
Hybrid Passenger Car on-board storage cost	**hybvst**
On board reformer cost (natural gas fuel cells passenger cars)	**gfcvst**
Hydrogen storage cost (hydrogen fuel cell passenger cars)	**hfcvst**
Hydrogen storage cost (hydrogen internal combustion engine cars)	**thyvst**

This is a sub-category of the perfect clustering technologies, in which the learning equations are applied only for the capital costs.

1.3.5. The Fuel Cell technologies

This group contains the following technologies:

Table 1-6: The fuel cell technologies

Technology Description	Technology Short Name
Gas Fuel Cell (generic stationary)	**gfc**
Hydrogen Fuel Cell (generic stationary)	**hfc**
Gas Fuel Cell Passenger Car	**gfcv**
Hydrogen Fuel Cell Passenger Car	**hfcv**

There is only one TFLC equation for the capital cost of all fuel cell technologies, which takes into account total installed capacity (mobile and stationary). The rationale behind this is that in the SAPIENTIA database, the fuel cell capital costs (measured in €99/Kw) are the same for both stationary and mobile applications. On the other hand, fuel efficiency, fixed O&M costs and variable O&M costs are different for the stationary and mobile applications and separate learning parameters have been estimated.

1.4. TFLCs Estimation

Particular attention has been given to the estimation of the TFLCs so as to ensure that apart from statistical fit they also displayed sufficient robustness for use in the wide variety of models and especially that they performed credibly in view of the R&D policy analysis. For the estimation historical time-series for R&D, equipment stock, capital costs and projections of technical and economic characteristics of technologies were used (as derived from the TECHPOL database), projections of installed equipment from the provisional POLES Baseline, projections of public and private R&D by technology elaborated by ICCS/NTUA, and finally cluster information from MARKAL. Clustering of technologies has been incorporated through learning by doing. The learning parameters were estimated by applying Maximum likelihood estimation over the historical period; yet this was by no means the only estimation criterion. All properties sought in the TFLCs specification figured among the objectives of the estimation. In addition, simultaneous equations estimation has also been applied (along clusters) in order to improve estimates and obtain appropriate co-variances of learning parameters. In all, technology dynamics have been estimated for a total of 51 technological options covering power generation, CO_2 capture and sequestration, Hydrogen-related technologies, conventional and non-conventional vehicles and Fuel Cells. Learning parameters were estimated for capital costs, fixed Operation and Maintenance costs, variable Operation and Maintenance costs, efficiencies and CO_2 capture rates.

The following table provides some TFLCs estimates for a selection of technologies.

Table 1-7: TFLCs estimates for selected technologies

	Capital Cost		FOM		VOM		Efficiency	
	Learning by doing	Learning by Research	Learning by doing	Learning by Research	Learning by doing	Learning by Research	Learning by doing	Learning by Research
Cluster Matrix Technologies								
New Nuclear (4th Gen.)	**-0.187**	**-0.490**	**-0.112**	**-0.763**	**-0.059**	**-0.280**	**0.015**	**0.287**
Coal Conventional Thermal	**-0.111**	**-0.013**	**0.000**	**-1.007**	**na**	**na**	**0.000**	**0.989**
Supercritical Pulvurised Coal	**-0.041**	**-0.089**	**0.000**	**-0.238**	**-0.079**	**-0.267**	**0.053**	**0.074**
Integrated Coal Gasification	**-0.027**	**-0.307**	**-0.057**	**-0.238**	**-0.018**	**-0.131**	**0.011**	**0.274**
Gas Turbine Combined Cycle	**-0.135**	**-0.655**	**-0.246**	**0.000**	**na**	**na**	**0.035**	**0.110**
Solar Thermal Power Plant	**-0.014**	**-0.474**	**-0.037**	**-0.226**	**na**	**na**	**na**	**na**
Biomass Thermal	**0.000**	**-6.554**	**-0.090**	**-0.234**	**na**	**na**	**0.015**	**0.097**
Biomass Gassification	**-0.020**	**-0.382**	**0.000**	**-0.502**	**na**	**na**	**0.080**	**0.449**
Hydrogen from Coal Partial Oxidation	**-0.018**	**-0.127**	**-0.061**	**-0.092**	**na**	**na**	**0.040**	**0.064**
Hydrogen from Biomass Pyrolysis	**-0.031**	**-0.046**	**-0.052**	**-0.077**	**na**	**na**	**na**	**na**
Stand Alone Technologies								
Building Integrated PV	**-0.206**	**-1.414**	**-0.172**	**-1.328**	**na**	**na**	**na**	**na**
Wind Turbine Onshore	**-0.085**	**-0.617**	**-0.058**	**-0.534**	**na**	**na**	**na**	**na**

Particular attention has been paid to the stochastic characteristics of the learning parameters, since they play a crucial role in determining the uncertainties surrounding the impacts of R&D actions that constitute an element for the integrated policy analysis performed at the end of the project. In general, learning by doing and learning by research parameter estimates within a single technology are strongly and negatively correlated, which tends to reduce variability of learning. Also, learning parameter estimates of the same type for different technologies within the same cluster tend to be positively correlated. This implies some uniformity in the stochastic behaviour of the whole cluster. Learning parameters also tend to be positively correlated when the same type of learning coefficient is considered (either learning by doing or learning by research). On the other hand, they tend to be negatively correlated when for example the learning by doing parameter for the capital cost is compared to the learning by doing parameter for the efficiency of the same technology.

Some examples on the correlation of learning parameters for a selection of technologies are presented in the following table.

Table 1-8: Correlation Matrix of Estimated Parameters

		CAPITAL COST									EFFICIENCIES						
		LEARNING BY DOING				LEARNING BY RESEARCH					LEARNING BY DOING				LEARNING BY RESEARCH		
	Techs	ICG	BGT	CPO	BPY	ICG	BGT	CPO	BPY	BF2	ICG	BGT	CPO	BF2	ICG	BGT	CPO
CAPITAL COST																	
LEARNING BY DOING	BGT	0.26															
	CPO	0.49	0.52														
	BPY	-0.07	-0.18	-0.17													
LEARNING BY RESEARCH	ICG	-0.70	-0.22	-0.40	0.11												
	BGT	-0.25	-0.84	-0.49	0.23	0.37											
	CPO	-0.41	-0.40	-0.83	0.21	0.54	0.60										
	BPY	0.05	0.18	0.17	-0.88	0.00	-0.14	-0.10									
	BF2	-0.03	-0.01	-0.05	-0.04	0.09	0.11	0.12	0.09								
EFFICIENCIES																	
LEARNING BY DOING	ICG	0.23	0.28	0.47	-0.07	-0.25	-0.28	-0.45	0.05	-0.03							
	BGT	0.32	0.62	0.55	-0.17	-0.32	-0.61	-0.51	0.13	-0.07	0.33						
	CPO	0.51	0.52	0.93	-0.16	-0.41	-0.48	-0.78	0.16	-0.06	0.45	0.54					
	BF2	0.03	0.17	0.08	-0.09	0.02	-0.13	-0.04	0.11	0.12	-0.02	0.10	0.08				
LEARNING BY RESEARCH	ICG	-0.19	-0.18	-0.38	0.13	0.31	0.33	0.52	-0.05	0.08	-0.77	-0.30	-0.36	0.00			
	BGT	-0.27	-0.48	-0.45	0.17	0.41	0.67	0.62	-0.06	0.14	-0.31	-0.88	-0.44	-0.06	0.40		
	CPO	-0.41	-0.39	-0.77	0.19	0.54	0.60	0.93	-0.10	0.12	-0.43	-0.50	-0.83	-0.04	0.51	0.61	
	BF2	-0.07	-0.16	-0.11	0.12	0.02	0.18	0.11	-0.12	-0.08	-0.04	-0.11	-0.10	-0.88	0.06	0.12	0.10

Finally, Table 1-9 below provides a classification of technologies with regard to their learning characteristics for capital costs as they emerged from the estimation. From the R&D policy point of view, the potentially most interesting technologies are those on the upper right corner of the table, where the fast and mostly learning-by-research technologies are presented. The technologies characterised by fast, balanced learning (new nuclear and photovoltaics) also have good prospects, as the impacts of R&D investment on these technologies (leading to enhanced competitiveness and take-up) are magnified by learning by doing at presumably no additional cost.

Table 1-9: Broad Learning Characteristics arising from estimated TFLCs

	Capital Costs		
	Mostly Learning by doing	**Balanced Learning**	**Mostly Learning by research**
Fast Learning	Hydrogen internal combustion engine passenger car	New Nuclear (4th gen.)/ Building integrated PV	Fuel Cell/ Wind turbines offshore/ Post-combustion CO2 capture (Supercritical pulverised coal)/ Pre-combustion CO2 capture (Integrated gasification combined cycle)
Medium Learning	Nuclear (2nd and 3rd gen.)/ Cogeneration from gas/ Post-combustion CO2 capture (Gas turbine combined cycle)	Hydrogen from Biomass Pyrolysis/ Hydrogen from Nuclear High-temperature Thermochemical Cycles/ Hydrogen from Water Electrolysis and dedicated Nuclear power plant/ Pre-Combustion CO2 capture(Coal Partial Oxidation)/ Large Hydro/ Supercritical pulverised coal/ Electric passenger car/	Hydrogen from Coal Partial Oxidation/ Hydrogen from Solar High-temperature Thermochemical cycles/ Oil fired Open cycle gas turbine/ Wind turbines Onshore/ Solar Thermal power plant cylindro-parabolic/ Biomass thermal/ Biomass gasification plus combined cycle/ Hybrid passenger car
Slow Learning	Hydrogen from Gas Steam Reforming (large scale)/ Lignite conventional thermal/ Coal conventional thermal/ On board reformer cost (Natural gas fuel cells passenger cars)/ Hydrogen storage cost (hydrogen fuel cell passenger cars)	Gas turbine open cycle	Hydrogen from Water Electrolysis (baseload electricity from Grid)/ Pre-Combustion CO2 capture (Gas Steam Reforming)/ Integrated coal gasification/ Oil conventional thermal/ Gas conventional thermal/ Gas turbine combined cycle/ Small hydro (<25MW)/ CO2 sequestration

The table above is indicative and should be viewed with caution. The ultimate success of R&D action on a particular technology not only depends on its learning characteristics, but also on the general context defining the market for this technology. This is determined by a host of factors including competition with other technologies, evolution of fuel prices, the intensity or lack of climate policy, overall and regional activity levels that determine the rate of technological renovation etc. This context can be quantitatively examined only through integrated models of the whole energy system.

C. Model Extensions in the context of the SAPIENTIA project

I. Sustainable Development Objectives

Asami Miketa and Ger Klaasen (1) **IIASA**
Denise Van Regemorter (2) **CES/KUL**
Markus Blesl, Ulrich Fahl and Anjana Das (3) **IER**

1. Relevant Sustainable Development Objectives

1.1. Introduction

This section aims to identify appropriate and measurable sustainable development indicators and their link with specific technological options, so that a whole chain from technology take-up to impacts on sustainability can be built, and collect the necessary data for this purpose. The integrated R&D policy analysis that is one of the main results of this project focuses on the evaluation of impacts on the basis of the sustainability objectives and the causal relationships defined under this section.

This report addresses the first part of the WP's objectives: identification of the R&D objectives to be used in the SAPIENTIA project. In doing so, we review sustainable development indicators used in the EU policy context so that we can have coherent coverage of sustainable development-related indicators in our list of R&D objectives.

The major task here is to develop objectives that can be measured in an explicit way. Hence this Task attempts to produce concrete definitions of each objective – initially one or two definitions per indicator, to be tested in the course of the project in order to eventually keep one definition for each indicator. In each case measurable indicators will be selected, under the provision that there are data available to 'translate' the current output of energy models to these indicators.

1.2. European Union strategy for sustainable development

The *SAPIENT* project considered objectives of R&D policy of a rather conventional nature. These included a measure of profitability, carbon dioxide emissions, energy cost reductions, security of hydrocarbon supply and tentatively direct employment creation. However, with the exception of the objectives on CO_2 and the Security of energy supply, the issues of sustainable development, which have been receiving more attention on the political agenda over the last decade, were not addressed. Since the incorporation of sustainable development objectives is likely to render the energy R&D policy exploration much more relevant to current R&D policy concerns, in SAPIENTIA it is envisaged to include a wide range of sustainable development indicators, covering most of the key areas identified in the Communication from the Commission 'A Sustainable Europe for a Better World: A European Union Strategy for Sustainable Development' (CEC, 2001a) which constituted a proposal to the Göteborg European Council and is largely reflected in the Presidency Conclusions (Göteborg European Council, 2001).

1.2.1. Introduction of the SD policy to the European Union

Göteborg European Council was a politically significant event for the EU in that it sets the basis for European Union's sustainable development policy. In the council, it was acknowledged that sustainable development should be integrated into various policy areas and agreed on a strategy for sustainable development based on proposals made by the Commission in its Communication "A Sustainable Europe for a Better World" (CEC, 2001a). The political significance of the Göteborg Council lies in the fact that the "environment" was added as the third dimension to the Lisbon Strategies. The Lisbon strategy is the "bold and ambitious" ten year goal of the European Union set at the Lisbon European council in March 2000, to make the Union "the most competitive and dynamic knowledge-based economy in the world, capable of sustainable economic growth with more and better jobs and greater social cohesion" (Lisbon European Council, 2000). At the Göteborg Council, it agreed 'a strategy for sustainable development which completes the Union's political commitment to economic and social renewable, adds a third, environmental dimension to the Lisbon strategy and established a new approach to policy making'. In this report, we refer to this strategy as the Göteborg sustainable development strategy.

The focal areas for the new environmental dimension identified in the Göteborg sustainable development strategy (CEC, *op. cit.*) include the following four areas: combating climate change, addressing threats to public health, ensuring sustainable transport, and managing natural resources more responsibly. Among non-environmental related issues, "combating poverty and social exclusion", and "dealing with the economic and social implications of an aging society" are also identified as the focal areas for the sustainable development in Europe. These two issues were, at the same time, already an integral part of the Lisbon Strategy. The following list the concrete objectives for each of the six focal areas as identified in the Göteborg sustainable development strategy.

Combating Climate Change

- The EU will meet its Kyoto commitment. After Kyoto, EU will reduce atmospheric greenhouse gas emissions by an average of 1% per year over 1990 levels up to 2020.
- The Union will insist that the other major industrialize countries comply with their Kyoto targets.

Addressing threat to public health

- Make food safety and quality the objective of all players in the good chain.
- By 2020, ensure that chemical are only produced and used in ways that do not pose significant threats to human health and the environment.
- Tackle issues related to outbreaks of infectious diseases and resistance to antibiotics.

Ensuring sustainable transport

- Decouple transport growth significantly from growth in GDP in order to reduce congestion and other negative side-effects of transport.
- Bring about a shift in transport use from road to rail, water and public passenger transport so that the share of road transport in 2010 is no greater than in 1998.
- Promote more balanced regional development by reducing disparities in economic activity and maintaining the viability of rural and urban communities, as recommended by the European Spatial Development Perspective.

Manage natural resources more responsibly

- Break the links between economic growth, the use of resources and the generation of waste.
- Protect and restore habitats and natural systems and halt the loss of biodiversity by 2010.
- Improve fisheries management to reverse the decline in stocks and ensure sustainable fisheries and healthy marine ecosystems, both tin the EU and globally.

Combat poverty and social exclusion

- Make a decisive impact on the eradication of poverty.

- Raise the employment rate to 67% for January 2005 and to 70% by 2010; increase the number of women in employment to 57% for January 2005 and to more than 60% by 2010.
- Halve by 2010 the number of 18 to 24 year olds with only lower secondary education who are not in future education and training.

Deal with the economic and social implications of an ageing society

- Ensure the adequacy of pension systems as well as of health care systems and care of the elderly, while at the same time maintaining sustainability of public finances and inter-generation solidarity.
- Address the demographic challenge by raising employment rates, reducing public debt and adapting social protection systems, including pensions systems.
- Increase the average EU employment rate among older women and men (55-64) to 50% by 2010.

1.2.2. Sustainable development indicators

A commonly accepted sustainable development indicator(s) set for the EU does not exist, and efforts have been made to establish some. In 2002, an SD indicator task force was formed to come up with a set of indicators that fit to the EU's sustainable development strategy (Eurostat, 2003). The departing point for the establishment of SD indicator sets was the "structural indicators" from the Lisbon strategies. The structural indicators are used as a basis to evaluate implementation of the Lisbon strategy. In order to build an effective review of the progress towards the goal of the strategy, the indicators are published in the Commission's annual Spring Reports. The list of the structural indicators are reviewed and refined by the Commission and agreed upon at the Council each year.

Following the agreement on sustainable development strategy at the Göteborg Council, an environment section with seven indicators was added, giving a total of forty two structural indicators on which to base the evaluation of progress towards the Lisbon goals and progress in implementing the Göteborg sustainable development strategy.

In the Spring Report 2003, 42 structural indicators were used together with a more detailed list of 107 indicators (CEC, 2003a). They are divided into the following 6 areas and each consists of 7 structural indicators;

(1) General economic background
(2) Employment
(3) Innovation and research
(4) Economic reform
(5) Social cohesion
(6) Environment

The 42 indicators used in the Spring Report 2003 are summarized in Table 1-1: below. Indicators related to the above-listed focal areas for the Göteborg sustainable development strategy appear mainly under the headings of employment, social cohesion, and environment.

Table 1-1: Structural indicators used in the Spring Report, 2003 (CEC, 2003a).

Indicator	Indicator
General economic background a. GDP b. Labor productivity c. Employment growth d. Inflation rate e. Unit labor cost growth f. Public balance g. General government debt	**III. Economic reform** 1. Relative price levels and price convergence 2. Prices in the network industries 3. Market structure in the net work industries 4. Public procurement 5. Sectoral and ad hoc state aids 6. Market integration 7. Business investment
I. Employment 1. Employment rate and employment rate of older workers 2. Average exit age from the labor force 3. Gender pay gap 4. Tax rate on low-wage earners 5. Life-long learning 6. Accidents at work 7. Unemployment rate	**IV. Social cohesion** 1. Inequality of income distribution 2. At-risk-of-poverty rate before and after social transfers 3. At-persistent-risk-of-poverty rate 4. Dispersion of regional employment rates 5. Early school-leavers 6. Long-term unemployment rate 7. Unemployment rate
II. Innovation and research 1. Public expenditure on education 2. R&D expenditure 3. Level of internet access 4. Science and technology graduates 5. Patents 6. Venture capital investments 7. ICT investment	**V. Environment** 1. Greenhouse gases emissions 2. Energy intensity of the economy 3. Transport 4. Urban air quality 5. Municipal waste 6. Share of renewable energy 7. Protection of natural resources

In the domain of environment, intensive reviews on the structural indicators have been made since 2001, reflecting the Council's urge to improve them so that they can give an adequate picture of the environmental issues affecting sustainability. A number of environment-related indicators, which were drawn up by the Council as an open-list, were reviewed, and in 2002, the Commission submitted a report to the Council, "Analysis of the 'open-list' of environment related headline indicators" (2002c). The review focused on the methodology and data availability for the indictors on the open-list. The open-list includes 34 indicators under four environment-related focal areas as identified in the Göteborg Council. The indictors included in the open-list are summarized in Table 1-2. Some of them are those already included in the current structural indicator set as published in the Spring Report 2003. The above-mentioned Task Force on sustainable development indicators was set up following the same line and started to examine the feasibility of the indicators on the 'open-list'. The final report on this is foreseen late in 2004.

Table 1-2: Open-list of environment-related headline indicators.

Combating climate change
1. Greenhouse gases emissions and carbon intensity of GDP
Ensuring sustainable transport/mobility
2. Transport intensity of GDP
3. Modal split of transport
4. Exposure of the population to high levels of transport noise
5. Average journey length and timer per person, by mode and purpose
6. Investment in transport infrastructure by mode (passengers and freight)
7. Internalization of the external costs
8. Fuel consumption for transport
Addressing threats to public health
9. Urban and rural population exposure to air pollution
10. Emissions of ozone precursors (NO_X) and MNVOC), particulate matters and SO_X
11. Exposure to toxic chemicals, including pesticides
12. Consumption of toxic chemicals, including pesticides
13. Public health indicators (not specified yet)
Managing natural resources more responsibly
14. Municipal waste collected and landfilled, related to GDP
15. Municipal waste collected incinerated and landfilled (including breakdown of energy recovery)
16. Waste prevention
17. Recycling rate of selected materials (glass and paper/cardboard)
18. Recycling rate of selected materials (extended to other materials)
19. Valorisation rate of selected materials
20. Hazardous waste generated
21. Sustainability of fishing for selected species in EU marine waters
22. N and P concentrations in rivers
23. Discharges of pollutants (nutrients, organics, chemicals) in water (pressure indicator)
24. Quality of drinking water
25. Water use by sector
26. Resources productivity indicators or Material intensity (GNP/Total Material Requirement) (by type of resource)
27. Intensity of material use (economy-wide)
28. Biodiversity index
29. Protected areas (for biodiversity)
30. Pesticides consumption
31. Organic farming
32. Nitrogen balance
33. Evolution of land use by main categories (proxy: Evolution of built-up areas)
34. Contaminated and eroded soils

1.3. Refining the indicators included in the SAPIENT project

R&D objectives considered in the SAPIENT project included a measure of future technology sales/profitability, cumulative carbon dioxide emissions, benefits to energy consumers in terms of cost reductions, security of hydrocarbon supply and tentatively direct employment creation. In the light of the experience gained from *SAPIENT*, some of these objectives are reviewed and refined in SAPIENTIA in the present section. Such sustainability-related objectives are climate change, Security of energy supply, and employment impacts.

(a) Climate change

Climate change is one of the six focal areas identified in the strategy for sustainable development at the Göteborg Council (CEC, 2001a). In the strategy, it was acknowledged that emissions of greenhouse gases from human activities are causing global warming, and was recognized that climate change is likely to cause more extreme weather events (hurricanes, floods) with severe implications for infrastructure, property, health and nature. An indicator on "the total green house emissions" is included in the structural indicators from the Spring Report 2003 as well as the open-list of environment related headline indicators. Although they include all six GHGs addressed in the Kyoto Protocol, here we will focus on the three main GHGs, namely, CO_2, CH_4, and N_2O, because the available models could only calculated the R&D shocks on these three indicators. Nonetheless, other three gases are included in the calculation of the indicators to maintain the policy relevance with respect to the Kyoto Protocol.

Neither the structural indicators nor the open-list of environment-related headline indicators include global indicators because the country/regional perspective is relevant for such policy-driven indicators. In light of the SAPIENTIA project, however, the global perspective is very relevant. Thus we agreed in the project's meeting at IIASA in June 2003 to include three additional indicators which capture global and long-term nature of sustainable development issues. They are; greenhouse gas concentrations, average temperature change and sea level rise.

• **Total greenhouses emissions:** percentage change since base year, index base year = 100, based on CO_2 equivalents (as defined in the structural indicator).

In the Spring Report 2003, the indicator is calculated as thousands tons of CO_2 equivalent of CO_2, N_2O, CH_4, HFCs, PFCs and SF_6, weighted by their global warming potentials according to the 1996 IPCC guideline for parties to the Climate Change Convention. GWPs used for the calculation are: carbon dioxide=1, methane=21, and nitrous oxide=310, sulfur hexafluoride=23900. Greenhouse gas emissions are estimated annually by all Parties and reported to the European Commission and to the UNFCCC, applying standard guidelines and reporting format. Historical CO_2 emissions from fossil-fuel burring, cement manufacture and gas flaring for the period 1751-2000 are reported by Marland *et al.* (2003) for most of the countries in the world.

• **Greenhouse gas (GHG) concentrations:** expressed in terms of parts per million (ppm) for CO_2; parts per billion (ppb) for CH_4 and N_2O; parts per trillion (ppt) for HFCs, PFC, and SF_6.

Time series data on those indicators are available from on-line database at the Carbon Dioxide Information Analysis Center (CDIAC, 2003). For further discussion on the data, we refer to the attached contribution from IIASA-ECS for WP2 (Barreto, 2003).

• **Average temperature change**: expressed in terms of Celsius (Cº).

Time series data on those indicators are available from on-line database at the Carbon Dioxide Information Analysis Center (CDIAC, *op .cit.*). For further discussion on the data, we refer to the attached contribution from IIASA-ECS for WP2 (Barreto, *op .cit.*).

• **Sea level rise**: expressed in terms of millimeter per year.

Time series data on this indicator is collected and presented in IPCC (2001). The data is limited and rough. As discussed in the contribution from PSI for the SAPIENTIA project (Kypreos, 2003), we could use the proportional relationship that sea level raises 7 centimeters per degree Celsius.

(b) Security of energy supply

Security of supply is addressed as one of the three traditional objectives (security of supply, competitiveness, and protection of the environment) of energy policy that are encompassed in the sustainable development, in the EU's report on the integration of environment and sustainable development policy for the *Energy* Council for the preparation of Göteborg strategy (CEC, 2001b).

SAPIENT addressed "Security of energy supply" with the aid of an indicator expressing the difference between the maximum increase in oil and gas prices in a 3-year period after a 'R&D shock' has been introduced and the corresponding increase in the reference case. This was a quite rough approximation, and in the frame of SAPIENTIA it was envisaged to refine this definition and thereby incorporate more appropriate indicators for Security of energy supply. In the project's meeting at IIASA in June 2003, it was agreed to add two more indicators to the list; reserves-to-production ratio and import dependency. Additionally, we propose to include reserves-to-consumption ratio to better reflect the Security of energy supply issue in Europe.

• **Price effect on the oil and gas:** in terms of percentage increase (in a three year period) in oil and gas prices.

This indicator was included in the *SAPIENT* project as an approximation of Security of energy supply based on an assumption that the higher energy price would correspond to the scarcity of energy. *Xx: true?* Oil and gas prices are available from *Energy Prices and Taxes* of the International Energy Agency (IEA, 2003). We propose to calculate composite index by combining the oil and gas price with consumption weights. However this indicator might be redundant given that two additional indicators below are available to capture the essence of the security of energy supply.

- **Reserves-to-Production (R/P) ratio or Reserves to Consumption (R/C) ratio:** in terms of the expected life of fossil fuel supplies or fuel consumption; oil and gas.

R/P ratio and R/C ratio are calculated by dividing reserves remaining at the end of any year with annual production or consumption of that year. They approximate years that the current level of production or consumption could be operated or sustained on the reserves. Reserves refer to those occurrences that are identified and measured as economically and technically recoverable with current technologies and prices. Naturally, with technological progress and prices down associated with it, the estimate of the reserves changes over time. Dividing it either with annual production or annual consumption gives expected life of fuel suppliers or fuel consumption. Whereas R/P ratio is relevant globally, R/C ratio appears more relevant to the EU countries, reporting a region's capacity to sustain consumption using only dependence, indigenous resources, and hence also provides information on the region's dependence on imported fossil fuels. All data is found in *BP Statistical Review of World Energy* (BP, 2003).

- **Import dependency of fuels:** in terms of share of import in total fuel consumption for the specific fuel, i.e., oil, and gas (as defined in the *Energy, transport, and environmental indicators – Data 1990-2000 Pocketbook* (EC, 2003)[4], hereafter "Pocketbook").

Energy dependency shows the extent to which a country relies on imports of a fuel in order to meet its energy needs. It is calculated using the following formula: net imports / (gross inland consumption +bunkers[5]) for the specific fuel. Data is available from the IEA's *Energy Statistics and Balances* (IEA, 2003).

(c) Employment impacts

Employment is the key element in the Göteborg sustainable development strategy as well as in the overall Lisbon strategy. The 2003 Spring Report includes two employment-related structural indicators; total employment growth (annual percentage change in total employment) and total employment rate (Employed person aged 15-64 as a share of the total population aged 15-64). However in the SAPIENTIA project, we decided not to address the employment impact due to the data availability on the modeling side (SAPIENTIA meeting at IIASA in June 2003).

1.4. Additional sustainability-related indicators

In addition to the indicators already considered in the *SAPIENT* project, further sustainability-related indicators are defined here in order to be able to quantify the impact of R&D on additional sustainable development issues. These indicators cover the area of health concerns (notably those arising from environmental degradation associated with energy production and use), pressure on natural resources, transport congestion, measures of social exclusion and regional imbalances. Based on the availability of the indicators from energy models included in the SAPIENTIA project, we focus on the following three narrower-defined areas; air pollution-related indicators on heath damage, transportation related indictors, and regional imbalances within EU related indicators regarding energy issues.

---

[4] This publication is a successor of the former pocketbook *Integration Indicators for Energy*, which addressed the sustainable development issues in the Energy area.

[5] Bunkers are defined as "quantities supplied to sea-going ships".

(a) Air pollution/Damages on public health

"Damages on public health" is one of the focal areas of the Göteborg strategy. Although the Göteborg strategy did not directly address the issue related to public health due to pollution, the "open-list of indicators" included several pollution-related indicators under the heading of "threats to public health". In the structural indicators, indictors on urban air quality represented by ozone and fine particulates are included. As to the direct health effect (mortality and morbidity) of air pollution, we rely on estimates available from ExternE project (Von Regemorter, 2003).

Ozone concentration could cause not only serious health problems but also damage to ecosystems, agricultural crops and materials. In the SAPIENTIA project, however, we only address the human health related indicators, due to the data limitation of the energy models.

- **Urban air quality:** population exposure to air pollution by ozone/by particulate matter, expressed in terms of percentages of urban population potentially exposed to concentration levels exceeding target/limit values for the protection of human health in a calendar year (as defined in the structural indicator).

The target value of ozone for the protection of human health is 120 $\mu g/m^3$ (maximum daily 8 hour mean). The limit value for fine particulates (PM_{10}) is 50 $\mu g/m^3$ (24 hour average) not to be exceeded on more than 35 days per calendar year. The policy target set in EC legislation is to achieve these target/limit values from 2010 and 2050 for ozone and fine particulates respectively. Data air quality related data is stored in the European air quality database AirBase accessible via http://etc-acc.eionet.eu.int/databases.

In *2002* Spring Report, alternative definition of the indicator was used. It was *number of days* of pollution exceeding the quality thresholds for each of the two selected air pollutants. Threshold used here was 110 $\mu g/m^3$ for ozone and 50 $\mu g/m^3$ for PM_{10} concentrations.

- **Mortality change due to air pollution:** expressed in terms of mortality rate.

The mortality rate is calculated using dose-response function slopes, which give percentage changes in mortality rate per $\mu g/m^3$ and both acute and chronic effects are calculated. For a description on dose-response functions, we refer to the attached contribution from KUL for WP2 (Von Regemorter, *op. cit.*).

"Years of life lost resulting from the emissions of one kilo-tonne of pollutant" is suggested as an alternative definition of the indicator by Das and Fahl (2003).

- **Morbidity due to air pollution:** expressed in terms of cases per year.

The morbidity is calculated using dose-response function slopes, which give units of cases per year per person per $\mu g/m^3$ and both acute and chronic effects are calculated. For description on dose-response functions, we refer to the attached contribution from KUL for WP2 (Von Regemorter, *op. cit.*).

"Restricted activities days resulting from the emissions of one kilo-tonne of pollutant" is suggested as an alternative definition of the indicator by Das and Fahl (2003).

(b) Transportation/congestion

Ensuring sustainable transportation is one of the focal areas in the Göteborg sustainable development strategy. Originally we planned to address the issue of congestion directly by the use of a congestion index or person-hours lost due to congestion. However, due to the limitation on the modeling side, we have decided, at the project's meeting in June, 2003 at IIASA, to take a more general view on transport, which is consistent to the Göteborg sustainable development strategy. The list of structural indicators includes two transportation related indicators: modal split of transport and volume of transport relative to GDP. We agreed on the indicators on the modal split, but we did not discuses the indicators on volume of transport relative to GDP.

One further point that we did not discuss at the SAPIENTIA June meeting (at IIASA) was an introduction of clean transportation technologies. We propose here to include an indicator on "hydrogen car introduction" as a sustainability indicator to be used as R&D objectives in the SAPIENTIA project, given the high policy relevance that it has for the European Commission.

Such an indicator, directly related to energy technology and R&D, appears more relevant to the scope of the SAPIENTIA project.

• **Percentage of road transport:** percentage of road transport in total inland goods transport (in ton-kilometers) and percentage of passenger transport by car in total inland-passenger transport (in passenger-kilometers) both indexed on a single year (1995) (as defined in the structural indicator).

Inland transport here includes road, rail and inland waterways and air and sea transport are excluded due to their predominantly international nature and associated conceptual difficulty in dealing with the data on country bases. Global/regional data is available from Schafer (1995).

• **Introduction of fuel cell passenger cars:** Percentage of fuel cell vehicles in the passenger car sector.

Limitation to the passenger cars is due to the data availability on the modeling side. For detailed discussion, see Turton and Barreto (2003).

(c) Energy-related regional imbalances in the EU

In the SAPIENTIA project, we address the issue of "social cohesion", which is one of the main issues in the Lisbon strategy, from an energy perspective. Possible indicators we considered for capturing this aspect include energy costs and benefits, and energy use and transport activity/infrastructure per capita in each country. Based on the data availability on the modeling side, we decided, at the project's June IIASA meeting, to focus on the energy costs. More specifically, we agreed to include the following two indicators; energy system costs, and energy costs to the consumer. As the indicator on the energy costs to the consumer, we propose to use three indicators representing industry price, household price, and transportation price following the practice in the above mentioned "Pocketbook" (EC, 2003).

As to reflect the regional imbalances of these indicators, we propose that they are represented by taking the ratio between the highest and lowest value in a region in question. The regional scope depends on each models' regional resolutions.

• **Regional imbalances in energy system costs:** a ratio between two regions with highest and lowest sum of annualized investment cost, fuel cost, and operation and maintenance cost, expressed in Euro.

In terms of the measurability, energy system costs are the least "measurable" indicator among all the indicators proposed here. It is in hypothetical nature, in that it is calculated only as a result of a model, based on a set of assumptions specific to a given model. Therefore, there is no "historical" estimation of energy system costs available.

• **Regional imbalances in energy costs to the consumer:** an average ratio between two regions with highest and lowest VAT-free industrial fuel prices (Euro per GJ: residual fuel, natural gas and electricity price), tax-inclusive household fuel prices (Euro per GJ: natural gas, electricity, and heating gas/oil), and retail (tax-inclusive) prices of transport fuels (Euro per liter: unleaded gasoline and automotive diesel) (as defined in the *Pocketbook*).

These definitions of the end-use prices in the three sectors are more or less consistent with the energy end-use prices defined in the IEA's *Energy Prices and Taxes* (IEA, 2003). In *Energy Prices and Taxes*, end-user prices are prices actually paid, i.e., net of rebates and prices that include taxes which have to be paid by the consumer as part of the transaction and which are not refundable. Note that this excludes value added tax paid in many European countries by industry and commercial end-users for all goods and services (including energy) and that in these cases value added tax is refunded to the customers, usually in the form of a tax credit. However, IEA data applies this rule also to transportation fuels, whereas the "Pocketbook" shows the tax-inclusive prices of transport fuels.

1.5. Indicators proposed for SAPIENTIA and further points for discussion

Table 1-3 is a summary of the indicators that are proposed in this report. It includes all the indicators agreed at the project's meeting at IIASA in June, 2003 as well as a few additional indicators that we assess as relevant to the SAPIENTIA project. The list reflects the EU's policy priority for the sustainable development as is set by the Lisbon strategy as well as by the Göteborg Council.

Table 1-3: Indicators proposed for SAPIENTIA

Category	Indicators	Unit
Climate change	Total greenhouse emissions	Index, calculated based on CO_2 equivalent of the total of 6 GHGs
	Greenhouse gas concentrations	CO_2: Parts per million.
		CH_4: Parts per million.
		N_2O: Parts per million.
	Average temperature change	Degrees Celsius.
	Sea level rise	Millimeter per year.
Security of energy supply	Price of the oil and gas	Euro or index
	Reserves-to-production ratio or reserves-to-consumption	Reserves to production ratio: expected life of the oil supply.
		Reserves to production ratio: expected life of the gas supply.
		Reserves to consumption ratio: expected life of the oil consumption.
		Reserves to consumption ratio: expected life of the gas consumption.
	Import dependency	Oil: percentage share.
		Gas: percentage share.
Air pollution / damages on public health	Urban air quality	Percentage of population exposure to air pollution by ozone.
		Percentage of population exposure to air pollution by particulate matter.
	Mortality rate change due to air pollution.	Change in mortality rate, acute effect.
		Change in mortality rate, chronic effect.
	Morbidity change due to air pollution	Change in the cases per year, acute effect.
		Change in the cases per year, chronic effect.
Congestion / transportation	Percentage of road transport	Percentage share of the truck transport in total inland goods transport.
		Percentage share of the car transport in total inland passenger transport.
	Introduction of fuel cell passenger cars	Percentage share of fuel cell cars in the total passenger cars (stock).
Energy-related regional imbalances	Regional imbalances in energy system cost	A ratio between two regions with highest and lowest system cost (sum of annualized investment cost, fuel cost, and operation and maintenance cost, expressed in Euro).
	Regional imbalances in energy cost to the consumer	An average ratio between two regions with highest and lowest VAT-free industrial fuel prices (of residential fuel, natural gas and electricity: Euro per GJ).
		An average ratio between two regions with highest and lowest tax-inclusive household fuel prices (of natural gas, electricity, and heating gasoil: Euro per GJ).
		An average ratio between two regions with highest and lowest tax-inclusive retail price of transportation fuels (of unleaded gasoline and automobile diesel: Euro per litter).

"Price of oil and gas" under the security of energy supply might be dropped from the list because two additional indicators ("R/P ratio" and "import dependency") that capture the essence of the security of energy supply in a more direct manner.

In addition, the refinement of the definition of the indicators suggested above is necessary. Table 1-4 summarizes the availability of the indicators from the models of the SAPIENTIA partners. The definition should be checked with the data availability on the models' side in the next SAPIENTIA meeting. In particular, further refinements of the definition of the indicators on health appear necessary in the consultation with the participants.

Table 1-4: Availability of the indicators from the models of the SPAIETNTIA partners.

Group	**IIASA**	**IER**	**IEPE**	**ECN**	**KUL**	**PSI**	**ICCS-NTUA**
Main model name	**ERIS**	**TIMES**	**POLES**	**MARKAL**	**GEM-E3**	**GMM**	**PROMETHEUS**
Carbon Dioxide emissions							
GHG emissions	X	X	X	X[4.1]	X	X	X
GHG concentrations	X			X[4.2]		X	X
Average temperature change	X					X	X[7.1]
Sea level change	X					X	X
Energy security of supply							
Oil and gas price increase	X	X	X	X[4.3]		X	X
Reserves/production ratio	X	X	X	X		*[6.1]	X
Import dependency of fuels	X	X	X	X		X	X
Health							
Urban air quality				X[4.4]		*[6.2]	
Mortality/morbidity					X	*[6.2]	
Congestion/transport							
Road transport share	*[1.1]		X	X[4.5]		*[6.3]	X
Regional imbalances							
Energy systems cost (differences among regions)		X	X	X	*[5.1]	X	X
Energy cost to consumer (differences among regions)		X	X	X	*[5.1]	X	X

Notes:

1.1: IIASA reports on the proportion of fuel-cell vehicles in the passenger car sector.
4.1: total GHG and emissions per gas, except for fluorides
4.2: derived using IPCC SRES and TAR results
4.3: Marginal costs
4.4: partially, expressed in NO_X and SO_X emissions
4.5: ECN will also report on fuel cell car share
5.1: GEM-E3 is a macroeconomic level, so the results are at that level also
6.1: PSI has a fixed specification of maximum resources in GMM and we can only provide the Production to this resources-availability ratio
6.2: Here the total external cost due to local pollution will be defined once total externalities will be defined
6.3: The road transport share to demand will be defined as an exogenous input in GMM and while energy use for transport will be the model output.
7.1: PROMETHEUS produces also "highest increase in temperature over a decade as a measure of impacts on ecosystems".

1.6. The final list of sustainable development indicators

At the SAPIENTIA mid-term meeting in Brussels (24-25 February), the list of sustainable development indicators, as well as the definitions, was finalized and agreed upon. They are summarized below.

1. Climate change

a. *Greenhouse gas emissions*: changes of emissions between 2000 and 2050 (or 2100) separately calculated for CO_2 and CH_4. The global warming potentials used were based on the IPCC TAR report on the basis of a 100-year commitment horizon.

b. *Greenhouse gas concentrations*: changes in the concentrations between 2000 and 2050 (or 2100) separately calculated for CO_2 and CH_4.

c. *Average temperature change*: average change between 2000 and 2050 in terms of degrees Celsius.

d. *Maximum increase of temperature in any decade*: measured in terms of degrees Celsius.

2. Security of energy supply

a. *Maximum increase of oil and gas prices in any three-year period*: measured in money terms

b. *Reserves-to-production ratio for oil and gas*: remaining (ultimately recoverable) reserves, expressed in years, calculated separately for oil and gas.

c. *Import dependency*: percentage share of import in total domestic supply, calculated separately for oil and gas in 2050.

3. Transportation/Urban Environment

a. *Introduction of low emission passenger cars*: expressed in shares in total park.

4. European Consumer

a. *Energy/Electricity cost reduction to consumer*: expressed in Euro

5. Regional imbalances

a. *Energy/Electricity cost reduction to consumer in the Less Developed Countries*: expressed in Euro

6. Market/Economic Objectives

a. *Market impact*: A measure combining technology penetration and cost reductions

References

Barreto, Leonardo (2003). Indicators of Climate Change in MINIMA-SUD: Historical Time Series, Key Relationships and Key Uncertainties. IIASA's contribution to the MINIMA-SUD.

BP (2003) BP Statistical Review of World Energy 2003, June 2003, London.

Commission of the European Communities (CEC) (2001a). A sustainable Europe for a better world: a European Union Strategy for Sustainable Development, Communication from the Commission, COM (2001)0264 final, Brussels.

Commission of the European Communities (CEC) (2001b). Integrating Environment and Sustainable Development into Energy and Transport Policies: review report 2001 and implementation of the strategies. Commission Staff Working Paper. SEC (2001) 502, Brussels, 21.3.2001.

Carbon Dioxide Information Analysis Center (CDIAC) (2003). Trends Online: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center. Oak Ridge National Laboratory. U.S Department of Energy. Oak Ridge, Tennessee, US. <http://cdiac.esd.ornl.gov/trends/trends.htm>. November 27, 2003.

Commission of the European Communities (CEC) (2002c). Analysis of the 'open list' of environment-related headline indicators requested by the December Council. Report from the Commission to the Council. COM(2002) 524final, Brussels, 10.7.2002.

Commission of the European Communities (CEC) (2003a). Choosing to grow: knowledge, innovation and jobs in a cohesive society, Report to the Spring European Council, 21 March 2003 on the Lisbon Strategy of economics, social and environmental renewal. Com (2003) 5 final., Office for Official Publications to the European Communities.

Das, Anjana and Ulrich Fahl (2003). Sustainable Development Objectives. Contribution by IER to SPAIENTIA WP2.

European Communities (EC) (2003). Energy, transport, and environmental indicators – Data 1990-2000 Pocketbook, Luxembourg.

Eurostat (2003) A Framework for the Setting-up Sustainable Development Indicators in the European Union, Third meeting of the ESS Task Force on Methodological Issues for Sustainable Development Indicators.

Göteborg European Council (2001). Presidency Conclusions, 15, 16 June, 2001. SN 200/1/01 REV1.

International Energy Agency (IEA) (2003). Energy Prices and Taxes. Paris.

International Energy Agency (IEA) (2003). Energy Statistics and Balances. Paris.

IPCC (Intergovernmental Panel on Climate Change) (2001). Technical Summary. In: J. T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P. J. van der Linden and D. Xiaosu (eds.), Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, UK.

Kypreos, Socrates (2003). Estimating the Indicator for SPAIENTIA: Temperature Change and Sea Level Rise due to Climate Change. PSI's contribution to WP2 of SAPIENTIA.

Lisbon European Council (2001). Presidency Conclusions, 23 and 24 March, 2000.

Marland, G.,T.A. Boden, and R.J. Andres (2003). Global, Regional, and National Fossil Fuel CO_2 Emissions. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A. <http://cdiac.esd.ornl.gov/trends/trends.htm>. November 27, 2003.

Van Regemorter, Denise (2003). Sustainable Development Indicators Damage and Valuation from Air Pollution –from ExternE to modeling framework -. Contribution by CES to SAPIENTIA WP2.

Schafer, A., 1995: "Trends in Global Motorized Mobility, The Past 20 Years and Implications for the Next Century". IIASA Working Paper, WP-95-49, Laxenburg.

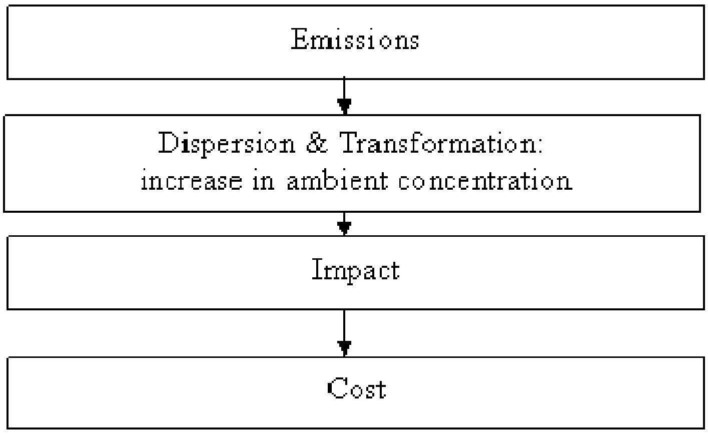
2. Damage and Valuation from Air Pollution

2.1. Introduction

The ExternE Project has developed a methodology for the evaluation of the impact of pollution linked to energy and has applied it to several case studies in various domains. The objective of this note is to describe how the data and methodology developed in ExternE can be used in the SAPIENTIA project to link emissions generated by technologies or by the economic activity in general (as output of energy models) to indicators related to health and air pollution.

The ExternE methodology, i.e. the 'impact pathway' approach, follows the sequence of events linking a 'burden' to an 'impact' and its subsequent valuation, as represented in the figure below.

Figure 2-1: An illustration of the main steps of the impact pathway methodology



The main data from ExternE to be used for this exercise are on one hand the dose-response functions and the valuation of the damage categories considered, mortality and morbidity changes and damage to forests, crops and materials, and on the other hand data linking emissions with soil deposition and air quality.

Though all these figures were and are still under much debate within the ExternE projects and, more generally, among scientists and policy makers, they can already, as they are, contribute to a better evaluation of the cost of air pollution and its policy implications. For a full discussion of the assumptions, limits and drawbacks of the approach one referred to the ExternE reports (1995 and 1998) and to R. Friedrich and P. Bickel (2001).

2.2. Impact on Health

2.2.1. Dose-response functions

The ExternE project retains, as principal source of health damages from air pollution, particulates resulting from direct emission of particulates or due to the formation of sulphates (from SO_2) and of nitrates (from NO_x), and ozone. They retain also a direct effect of SO_2 but no direct impact of NO_x because it is likely to be small.

In most studies the dose-response functions for ambient particles are expressed in terms of PM_{10}[6], but there is evidence that the relative fine particles (i.e. $PM_{2.5}$) are associated with greater risks than PM_{10} and there are no European studies evaluating dose response functions for these fine particles. Therefore ExternE derived $PM_{2.5}$ functions from the PM_{10} functions with a conversion factor of

---

[6] PM10, i.e. particulates of less than 10 $\mu g/m^3$ aerodynamic diameter

1.67 and adopted the following assumptions for quantifying the effects of the different particulate emissions[7]:

- each incremental μg/m³ of primary particles from power stations and of nitrates are treated as if it had the toxicity of PM_{10}
- each incremental μg/m³ of primary particles from transport and of sulphates are treated as if it had the toxicity of $PM_{2.5}$

Units

Though air pollution levels show substantial temporal and spatial variation, in ExternE, except for ozone, dose-response functions for chronic as well as acute effects are expressed in terms of annual average concentrations. By focusing on annual averages, the dose-response functions give no direct information about the relevance, for health, of short-term peak concentrations.

For ozone, evidence strongly supports the view that acute effects of ozone should be quantified but longer time frames are also relevant and the dose-response functions are expressed for 6-hour daily average.

Dose-response function slopes

Epidemiological studies give actually the slope of the dose-response function, i.e. the increase in cases of acute/chronic health effects and/or the increase in mortality per unit change in ambient pollution concentration. ExternE states dose- response slopes in units of cases per year per person per μg/m3, except for mortality which is expressed as percentage change in mortality rate per μg/m³ and considered both acute and chronic effect. When chronic mortality impacts are explicitly accounted for, one must exclude the acute mortality impacts because they are already considered in the former.

The values have been determined based on an extensive study of the epidemiological literature on the health effects of ambient air pollution. Table 2-1 show the values proposed by ExternE and which can be used in this modelling exercise[8]. ExternE gives also an uncertainty rating which could be used.

---

[7] The literature review conducted during ExternE suggests that the most severe health effects are associated with primary particulate emissions and the least severe with nitrates for given change in ambient concentration

[8] They are used in the GEM-E3 general equilibrium model and in MARKAL-Belgium, an energy optimisation model.

Table 2-1 Dose-response slopes for human health impacts *(in cases events per year per person per $\mu g/m^3$, except for mortality which is in percentage increase per $\mu g/m^3$)*

Receptor	Health endpoint	Reference	Pollutant	Slope	Uncertainty
ASTHMATICS					
Adults	Bronchilator usage	Dusseldorp et al., 1995	PM_{10}	0.163	B
			$PM_{2.5}$	0.272	B
	Cough	Dusseldorp et al., 1995	PM_{10}	0.168	A
			$PM_{2.5}$	0.28	A
	Lower respiratory symptoms (wheeze)	Dusseldorp et al., 1995	PM_{10}	0.061	A
			$PM_{2.5}$	0.101	A
Children	Bronchilator usage	Roemer et al., 1993	PM_{10}	0.078	B
			$PM_{2.5}$	0.129	B
	Cough	Pope and Dockery, 1995	PM_{10}	0.133	A
			$PM_{2.5}$	0.223	A
	Lower respiratory symptoms (wheeze)	Roemer et al., 1993	PM_{10}	0.103	A
			$PM_{2.5}$	0.172	A
All	Asthma attacks	Whittemore and Korn 1980	O_3	4.29E-03	B
ELDERLY 65+					
	Congestive heart failure	Schwartz and Morris, 1995	PM_{10}	1.85E-05	B
			$PM_{2.5}$	3.09E-05	B
CHILDREN					
	Chronic cough	Dockery et al., 1989	PM_{10}	2.07E-03	B
			$PM_{2.5}$	3.46E-03	B
	Chronic bronchitis	Dockery et al., 1989	PM_{10}	1.61E-03	B
			$PM_{2.5}$	2.69E-03	B
ADULTS					
	Restricted activity days	Ostro, 1987	PM_{10}	0.025	B
			$PM_{2.5}$	0.042	B
	Minor restricted activity day	Ostro and Rothschild, 1989	O_3	9.76E-03	B
					B
	Chronic bronchitis	Abbey et al, 1995	PM_{10}	2.45E-05	A
		(after scaling down)	$PM_{2.5}$	3.90E-05	A
ENTIRE POPULATION					
	Chronic Mortality	Pope et al., 1995	PM_{10}	0.13%	B
		(after scaling down)	$PM_{2.5}$	0.21%	B
	Respiratory hospital admissions	Dab et al., 1996	PM_{10}	2.07E-06	A
			$PM_{2.5}$	3.46E-06	A
			SO_2	2.04E-06	A
		Ponce de Leon, 1996	O_3	3.54E-06	A
	Cerebrovascular hospital admissions	Wordley et al., 1997	PM_{10}	5.04E-06	B
			$PM_{2.5}$	8.42E-06	B
	Symptom days	Krupnick et al.,	O_3	0.033	A
	Cancer risk estimates	Pilkington et al., 1997 based on US EPA evaluations	Diesel particles	4.86E-07	B
	Acute Mortality	Spix et al./Verhoeff et al., 1996	PM_{10}	0.04%	B
			$PM_{2.5}$	0.07%	B
		Anderson et al./Touloumi et al.,	SO_2	0.07%	B
		Sunyer et al., 1996	O_3	0.06%	B

Uncertainty: A=high confidence,σ_g=2.5 to 4; B=medium confidence,σ_g=4 to 6; C=low confidence,σ_g=6 to 12;

(a) Population by category

The effects of incremental air pollution on human health depend on the age of the affected persons and their state of health as can be seen in the table above. Consequently, estimates are needed for the percentages of people in each age and health group. The estimates used for the EU countries are:

- 14% of population is over 65 years old
- 20% of population is under 15 years old
- 80% of population is adult
- 3.5% of population is asthmatic

(b) Mortality rate

As the dose-response functions for mortality endpoints are expressed as percentage increase in mortality per additional μg/m³ of the pollutant considered, an estimate for the actual mortality rate is needed. ExternE 1998 as well as ExternE 2000 assume a mortality rate of 0.99% and this figure can be used for the EU countries.

2.2.2. Valuation of the health endpoints

(a) Valuation of mortality

The concept of value of statistical life (VOSL) and of year of life lost (VOLY)

The valuation in the first ExternE project was based on the concept of 'value of statistical life' (VOSL) which is derived in most studies from the estimation of the willingness to pay for a change in the risk of death. The WTP is then converted into the 'value of statistical life' (VOSL) by dividing WTP by the change in risk. Estimates of the WTP for a reduction in risk had been made by three methods. First, there were studies that looked at the increased compensation individuals needed, other things being equal, to work in occupations where the risk of death at work is higher. Thus, these studies provided estimates of the willingness to accept higher risks. Second, in CVM studies individuals were questioned about their WTP and WTA for measures that reduced or increased the risk of death from specific activities (e.g. driving). Third, researchers had looked at actual voluntary expenditures on items that reduce the risk of death from certain activities (e.g. airbags for cars). It is worth noting that, on average, the highest values came from the CVM studies and the lowest from the consumer market studies, where actual expenditures are involved. ExternE proposed an average estimate based on European studies equal to 3.14 million ECU 1995.

In the next ExternE project, there was a shift towards the concept of year of life lost (YOLL) to take into account the impacts of latency, manner of death, years of life remaining and other related factors. A framework was developed, through which an estimate of the value of life years lost could be derived consistent with the value of statistical life estimates. The relationship between value of statistical life (VOSL) and value of life year lost (VOLY) was taken as follows:

$$VOSL_a = VOLY_r \; \Sigma^{T}_{i=a+1} \; {}_aP_i \, (1+r)^{i-a-1} \qquad (1)$$

where a is the age of the person whose VOSL is being estimated, ${}_aP_i$ is the conditional probability of survival up to year i, having survived to year a. T is the upper age bound and r is the discount rate. Note that in this formula VOLY is assumed to be independent of age[9]. Taking the probabilities for male individuals aged 35 and 45, assuming a VOSL equal to 3.14 million ECU (1995) and using different discount rates, the following values were calculated. These values of VOLY were then used for the valuation of the mortality effects.

Table 2-2: VOLY for different discount rates in ECU (1995)

Discount rate	VOLY with age 35	VOLY with age 45
0%	84100	111600
3%	141100	168500
10%	301400	322400

Valuation of acute mortality effects

To estimate the costs of the mortality effects, ExternE recommended to use equation (1) with the proposed values for VOLY and replacing the normal conditional survival probabilities with the probabilities associated with the particular case. For acute mortality effects related to air pollution, they estimated the loss of life years to be on average about 0.75 years as most affected persons are old or unhealthy and have a short life expectancy. Thus, for acute effects the P_i's were replaced with 1 for the following 0.75 years and zero thereafter. Using the average of VOLYs with age 35 and 45, this resulted in estimated acute mortality costs of 73500 ECU 1995 (0 % discount), 116250 ECU 1995 (3 %) and 234000 ECU 1995 (10 %).

---

[9] The age dependency relation of the VSL and VOLY is amply discussed in ExternE.

Valuation of chronic mortality effects

For chronic effects the calculation was more complicated as, once exposed, the impacts can occur with a latency that is variable. Once the impact is underway, survival probabilities are altered. Although there were great uncertainties, the study team estimated, for representative populations, the number of years of life lost as a result of an increment in the hazard in year i, in each future year ($YOLL_i$). They estimated also for such a case the total number of years of life lost in the population ($YOLL_{tot}$). An average value of life years lost to be attached to a case of chronic mortality ($VOLY_{chronic}$) was then estimated as:

$$VOLY^{r}_{chronic} = \Sigma^{T}_{i=1} \quad \frac{YOLL_i}{YOLL_{tot}} * \frac{VOLY_r}{(1+r)^{i-1}} \qquad (2)$$

Equation (2) was used to estimate values for different chronic effects with different latency, $YOLL_i$ and $YOLL_{tot}$ values. The age distribution of the population used was that of the European Union and survival probabilities were those for Germany. Considering a latency and risk spread out evenly over 30 years as appropriate for chronic mortality arising from airborne particulate matter, the following figures were proposed as valuations for chronic mortality: 84330 ECU 1995 assuming a 3% discount rate and 98000 ECU 1995 assuming a 0% discount rate. For other chronic mortality endpoints (i.e. fatal cancers) valuation figures per mortality case were estimated, using the $VOLY^{r}_{chronic}$ values and estimates of the latency and years of life lost for the different endpoints.

Table 2-3: Estimates of mean years of life lost (YOLL) and subsequent valuation of fatalities for cases of different types of cancer (in ECU 1995)

Type of cancer	**Causative pollutants**	**Latency**	**Mean YOLL**	**Discount rate**		
				0%	**3%**	**10%**
Leukaemia	Benzene Butadiene	8 years	22	2160000	1570000	1180000
Lung cancer	PAHs Diesel particulates	15 years	16	1570000	1080000	418000
Stomach cancer	Ethylene oxide	15 years	15	1470000	992000	373000
Nasal cancer	Formaldehyde	20 years	14	1370000	848000	252000

As these cancers come with a long latency period, ExternE recommends to add a cost for the period of pain and suffering (estimated at 450000 ECU) in addition to the value of the life years lost. These different figures do not take into account the age dependency of the VOSL, as surrounded by too much uncertainty.

Valuation of mortality endpoints

Considering three mortality endpoints:

- acute mortality due to PM_{10}, $PM_{2.5}$, sulphates or nitrates
- chronic mortality due to PM_{10}, $PM_{2.5}$, sulphates or nitrates
- lung cancer due to diesel particles

the proposed mortality valuations as derived from the figures above and with a 0% discount rate are given in Table 2-4.

Table 2-4: Valuation of mortality endpoints (ECU 1995)

Endpoint	Valuation
Acute mortality	73 500 €
Chronic mortality	98 000 €
Lung cancer	2 020 000 €

(b) Valuation of morbidity endpoints

Valuation methodology

The underlying principle in the monetary valuation techniques for the endpoints is to obtain the willingness to pay of the affected individuals to avoid the negative impact, or the willingness to accept payment as compensation if a negative impact takes place. The willingness to pay for an illness, is composed of the following parts: the value of the time lost because of the illness, the value of the lost utility because of pain and suffering, and the costs of any expenditures on averting and/or mitigating the effects of the illness. To value morbidity endpoints, researchers have estimated the cost of illness (COI) and used contingent valuation methods and applied models of avertive behaviour for the other component. The COI are the easiest to measure, and can be derived from either the actual expenditures associated with different illnesses, or the expected frequency of the use of different services for different illnesses. The contingent valuation approach (i.e. surveys) is the only method that can estimate the value of pain and suffering, but the difficulties generally associated with any CVM study have to be coped with. Avertive behaviour models involve the estimation of a health production function, from which one is able to estimate the inputs used by the individual in different health states, and taking the difference in value between these to obtain the cost of moving from one health state to another.

Valuation of acute and chronic morbidity endpoints

For the valuation of morbidity effects ExternE used figures from the survey of the American literature and from EU projects on valuation of acute morbidity impacts (one in Helsinki (Otterström et al., 1998), one in Strasbourg and Kehl (Rozan, 1999) and a 5-country study in Amsterdam, Lisbon, London, Oslo and Vigo (CSERGE et al., 1999)). The last available figures from ExternE are given in Table 2-5.

Table 2-5: Acute and chronic morbidity valuations in ExternE

Acute morbidity endpoint	**ExternE value** **(in EURO 2000)**
Restricted activity day	104.0 €
Minor restricted activity day	41.0 €
Symptom day	41.0 €
Lower respiratory symptoms (wheeze)	8.0 €
Emergency room visit	597.0 €
Respiratory hospital admission	1766.0 €
Cardiovascular and other hospital admission	8421.0 €
Acute asthma attack / Bronchilator usage	37.0 €
One cough day	41.0 €

Chronic morbidity endpoint	
Chronic illness	1248000 €
Chronic bronchitis (adults)	112350 €
Non-fatal cancer	481500 €
Malignant neoplasms	481500 €
Chronic case of asthma	112350 €
Cases of change in prevalence of bronchitis (children)	241 €
Cases of change in prevalence of cough (children)	241 €

2.3. Impact on agriculture, forests and materials

Next to the impacts of pollutant emissions on public health, there are also the impacts of acidifying pollutants and ozone on agriculture, forests and materials. Acidifying emissions and ozone have negative effects on the yield of crops, cause damage to forests and can result in material loss, discoloration and structural failure.

2.3.1. The valuation methodology

As for the valuation of health impacts, the methodology applied in ExternE is to estimate the magnitude of the effects (endpoints) of pollution to materials, trees and plants by using dose-response functions and to associate cost values to the different endpoints. However because of the great uncertainty around existing data or the absence of data for some aspects makes it very difficult to derive an average cost estimate for the endpoints.

(a) Damage to agriculture

Dose-response functions were proposed to assess the direct impact of SO_2 and O_3 on the yield of a limited number of crops, the increased liming requirement to compensate for acid deposition was evaluated and the reduced nitrogenous fertiliser requirements through deposition of oxidised N was examined. However, a wide range of crops can be affected and adequate dose-response functions did not appear to be available for all of them.

Concerning the valuation of the impacts, the earliest crop damage estimate studies simply multiplied the reduction in output attributable to the pollutant by the market price. ExternE proposes to use the international prices in valuing the changes, although it should be seen as a very rough estimate.

(b) Damage to forests

From a literature review on dose-response functions and critical pollutant concentration levels to assess the impacts of pollutants on a number of plants and trees, it was very difficult to derive impact of pollution to forests. In addition, there are many difficulties in translating physical impacts to forests into monetary damages, because a significant portion of the total value of a forest is from non-market values, which are difficult to quantify. The various components to take into account for the value of the forests are timber value, recreational value, CO_2 uptake and storage, wildlife habitat, … . Quantification of forest damage is further complicated by issues of transferability of the results from one location to another. Besides, for the vast majority of forest valuation studies, no attempt could be made to establish an external marginal valuation for forestry based on per tonne of pollutant, as almost all the studies lack data on pollution levels.

(c) Damage to materials

Discoloration, material loss and structural failure, which result from interactions with acidifying substances like SO_2 and NO_X, particles and O_3, are the main impact categories for most materials. ExternE 1998 considered discoloration effects to be small and structural failure to be unlikely. Therefore, the analysis was limited to the effects of acidic deposition on corrosion and a methodology was proposed to assess the damage of acidic deposition to the common building materials used across Europe which was extended to the soiling of building in ExternE 2000. However it remains difficult to assess the damage to materials and associate a value and combine it into one cost estimate.

2.3.2. Possible Figures

Because of the great uncertainty around dose response functions and the valuation of the damages, it was impossible to derive a damage impact coefficient with a valuation term associated to it for each category of damage. Moreover, first results from ExternE showed that damage to crops, forests and materials were relatively less important than public health impacts and represented only approximately 25% of total health damage from particulates. Therefore, Mike Holland (ExternE, ETSU) and VITO computed an average cost per person[10] from ExternE detailed computations to be used as an indicative value. These average cost estimates are shown in Table 2-6.

---

[10] This exercise was done for its implementation in GEM-E3, but might need to be updated.

Table 2-6: Damage estimates for effects on crops, forests and materials

	ECU 1995	**Source**
Nitrites	0.0018	Mike Holland (ExternE, ETSU)
Sulphites	0.0028	Mike Holland (ExternE, ETSU)
Ozone	0.0008	Leo De Nocker (ExternE, VITO)

2.4. Impact of global warming

The impacts of global warming are diverse and potentially large. They include effects on a wide range of receptors: humans, animals, plants, forests, crops… The impacts on these receptors, however, are very uncertain, are longer term, and are not restricted to local or regional areas. Therefore, quantification of global warming damages is difficult.

Within ExternE, the Global Warming subtask sought to apply and extend the established ExternE methodology for marginal external costs to the climate change damages of greenhouse emissions. For this the existing climate change models FUND 1.6 (Tol, 1995, 1996), complemented later with the new FUND model 2.0 (Tol, 1999), and the Open Framework (Downing et al., 1995, 1996) have been used. Both models calculate greenhouse gas marginal damages by modelling greenhouse gas concentrations, estimating the resulting climate change and forecasting and valuing the impacts of the estimated climate change. The models have different structures and strengths and can thus increase the understanding of the global warming issue.

For the valuation of CO_2-impacts ExternE 2000 recommends as central estimate the values obtained with FUND 2.0 (Table 2-7) using a 'value of life years lost' for mortality valuation, equal to 10 times per capita income, per year lost. This approach leaded to substantially lower marginal costs than those obtained with the 'value of statistical life' methodology, which accorded to cases of mortality a value of 200 times per capita income.

Table 2-7: Damage estimates for CO_2 emissions recommended in ExternE 2000

	Minimum[b]	Low[c]	Central estimate[d]	High[c]	Maximum[e]
Damage in EURO 2000 /ton CO_2 [a]	0.1	1.4	2.4 (for impacts in entire world) 0.2 (for impacts in Europe only)	4.1	16.4

[a]: Model FUND 2.0. Time horizon 2100, scenario is IS92A. Morbidity risks are valued based on the value of a life year lost.

[b]: pure rate of time preference (discount rate) = 3% ; EU impacts only

[c]: high and low approximately span the 67% confidence interval

[d]: pure rate of time preference (discount rate) = 1% ; EU impacts plus impacts in other regions with globally averaged values

[e]: pure rate of time preference (discount rate) = 0% ; EU impacts plus impacts in other regions with EU values

There is still a lot of uncertainty in these figures; they can be completed with indicators such GHG concentration, global temperature change or global sea level rise to give a broader picture.

2.5. Transformation and transport of emissions

As the impact from air pollution is related to the air concentration, a link must be established between a change in emissions and the resulting change in concentration levels of primary and secondary pollutants. Moreover, the transboundary nature of pollutants leads to the necessity to account for the transport of SO_2, NO_x, VOC and particulates emissions between countries (or grids). In the case of tropospheric ozone (a secondary pollutant), besides the transboundary aspect, the relation between VOC and NO_x emissions, the two ozone precursors, and the level of ozone concentration has also to be considered.

Though models of atmospheric dispersion and of chemical reactions of pollutants evaluate this transport and transformation of pollutants, it is possible, given the objective of this project, to simplify the approach through linearization with transfer coefficients, reflecting the effect the emitted pollutants in the different countries have on the deposition/concentration of a pollutant ip in a specific grid/country, such as to measure the incremental deposition/concentration, compared to a reference situation.

Transport/deposition coefficients for SO_2 and NO_x emissions can be derived from EMEP budgets for airborne acidifying components which represents the total deposition at a receptor due to a specific source. For particulates, there are also estimates of country to country transfers of primary particulates. For tropospheric ozone which is a secondary pollutant formed in the atmosphere through photochemical reaction of two primary pollutants, NO_x and VOC, there are also EMEP linear source-receptor relationships. Finally, an estimated equation linking the deposition of a pollutant to air concentration is used to compute the change in air concentration. These different steps allow, in a rather simplified and aggregate manner, to compute the full chain from change in emissions to change in ambient air quality and in deposition of acidifying emissions.

2.6. From Primary Pollutant Emission to Damage

In fine, the objective is to represent the full chain from the primary emissions of a specific technology or as the output of energy models to the sustainable development indicators, damage to public health, agriculture, ecosystems and buildings, both in quantitative terms and in monetary terms, using the data described in the previous sections. Combining the two types of data:

1. the pollutants' transformation and transportation, i.e. the transboundary effect of emissions;
2. the value of the environmental damages caused by the incremental pollution compared to a reference situation in monetary terms.

One can compute a figure for the damage per unit of emission of a primary pollutant. The figure obtained is country specific because of the transboundary aspect and the difference in population density between countries. For some damage categories, this approach can be complemented with threshold indicators.

It must be remembered that the analysis based on this approach can only be conducted on a marginal basis, i.e. assessing the incremental effects and costs compared to a reference situation, and assuming constant marginal damage.

The table below gives the first result of this exercise. They are still at a very aggregate level and do not take into account the sectoral origin of the emissions.

Table 2-8: Damage per unit of emission (ECU95/kg pollutant)

	Public Health Damage				Other Damages		
	NOX	PM	SO2	VOC	NOX	SO2	VOC
Austria	1.590	8.592	1.217	0.069	0.180	0.114	0.014
Belgium	4.409	14.541	4.568	0.421	0.424	0.429	0.083
Germany	3.485	12.610	2.771	0.320	0.344	0.260	0.063
Denmark	1.286	5.988	0.947	0.099	0.146	0.089	0.019
Finland	0.322	2.468	0.161	0.009	0.041	0.015	0.002
France	3.752	10.647	2.509	0.184	0.423	0.236	0.036
Greece	0.334	3.361	0.226	0.024	0.039	0.021	0.005
Ireland	2.746	5.655	1.274	0.151	0.327	0.120	0.030
Italy	1.693	8.049	1.068	0.120	0.185	0.100	0.023
Netherlands	3.736	13.361	4.355	0.394	0.354	0.409	0.077
Portugal	1.463	5.019	0.734	0.136	0.176	0.069	0.027
Spain	1.411	6.830	0.820	0.028	0.160	0.077	0.005
Sweden	0.783	3.293	0.286	0.083	0.107	0.027	0.016
UK	2.512	9.533	2.360	0.298	0.237	0.222	0.059

References

EMEP (1996), “Transboundary Air Pollution in Europe”, MSC-W Status Report 1/96 (july).

European Commission (1995) ExternE Externalities of Energy. Vol 1 - Vol 6, Reports produced for the EU–DGResearch

European Commission (1998) ExternE Externalities of Energy. Vol 7 - Vol 10, Reports produced for the EU–DGResearch

Friedrich R. and P. Bickel, ed. (2001) 'Environmental External Costs of Transport' Springer Berlin

Gosh D., Lees D., Seal W. (1975) ‘Optimal Motorway Speed and Some Valuations of Time'

Holland, Mike (1997), “Transfer of ExternE Data to GEM-E3 and PRIMES”, mimeo

Tol R. (1999) ‘The Marginal Costs of Greenhouse Gas Emissions.’ Energy Journal 20, pp. 61-81.

Tol R. (1995) ‘The Damage Costs of Climate Change Toward More Comprehensive Calculations.’ *Environmental and Resource Economics 5, pp. 353-374.*

Tol R. (1996) ‘The Damage Costs of Climate Change Towards a Dynamic Representation’ *Ecological Economics 19 pp. 67-90*

3. Integration of SD Objectives into the models

This report addresses two tasks undertaken by IER:

- Establishing causal chains from technology take-up to indicators
- Data collection for measurement of sustainable development indicators and causal chains

A report prepared by IIASA identified a range of sustainability indicators in the areas of socio/macro-economic, energy, transport, climate, and health and pollution (Klaassen and Miketa, 2003). In the IIASA meeting on June, 2003, partners selected the following indicators for further consideration in the study (Table 3-1).

Table 3-1: Selected indicators

Indicators	Type
Green house gas emissions	Climate
Green house gas concentrations	Climate
Global temperature change	Climate
Global sea level rise	Climate
Energy system costs	Energy
Energy costs to the consumer	Energy
Security of energy supply	Energy
1. Import dependence	Energy
2. Depletion of resources-	Energy
Congestion index	Transport
Mortality change due to air pollution	Health and air pollution
Morbidity change due to air pollution	Health and air pollution
Monetary damage to crops, materials etc.	Health and air pollution

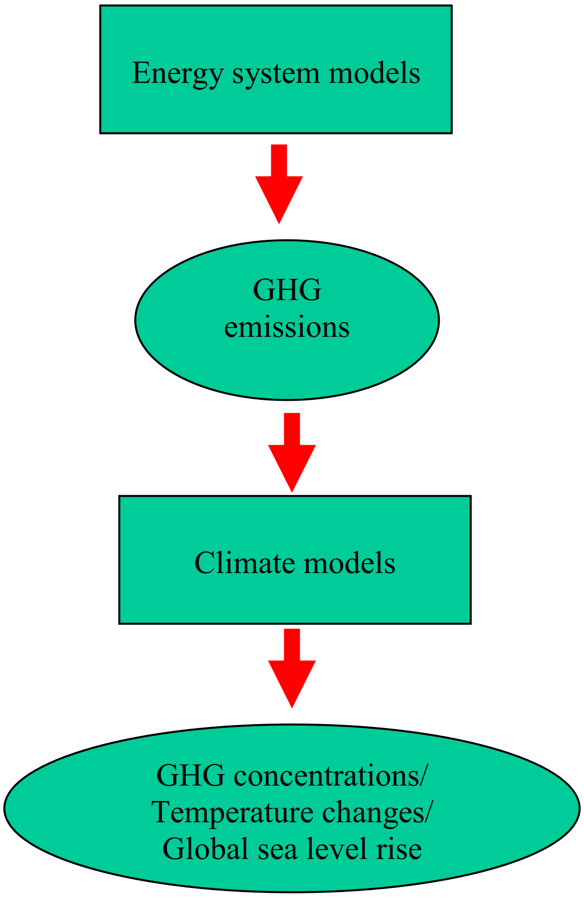
Remaining part of the report discusses how these indicators are measured and linked with the models and corresponding data availability.

3.1. Measuring and linking the indicators with the model

We discuss the indicators by category how they are to be measured and linked with the models depending upon the data availability in the following sections:

3.1.1. Climate Indicators

Figure 3-1: Modeling linkage for climate indicators



Indicators considered in this category are, 1)greenhouse gas emissions, 2) green house gas concentrations, 3) global temperature change and 4) seal level rise. Green house gas emissions is a model estimate, all energy system models at its current state, estimate it. The remaining indicators are dependent on the green house gas emissions and need climate models to estimate them (Figure 3-1).

Figure 3-2 Climate indicators in A1B Scenario

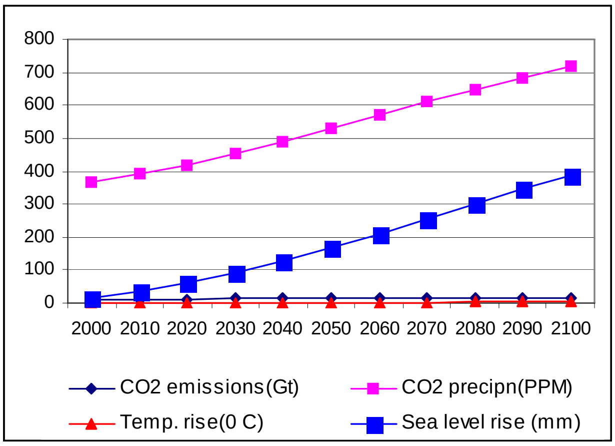
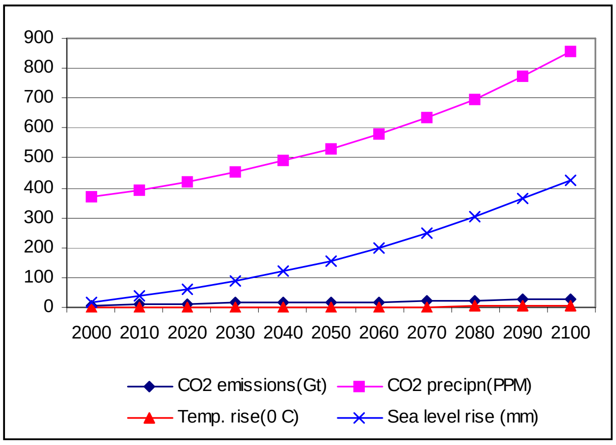


Figure 3-3: Climate indicators in A2 Scenario



In 1996, the IPCC began the development of a new set of emissions scenarios, effectively to update and replace the well-known IS92 scenarios (IPCC, 1994). The approved new set of scenarios is described in the IPCC Special Report on Emission Scenarios (SRES) (IPCC, 2000). Four different narrative storylines were developed to describe consistently the relationships between the forces driving emissions and their evolution and to add context for the scenario quantification (Annex 1). A number of energy system models or impact assessment models such as, AIM, MESSAGE, IMAGE etc. are used to assess the future emissions of greenhouse gases under these scenarios.

Figure 3-4 :Climate indicators in B1 Scenario

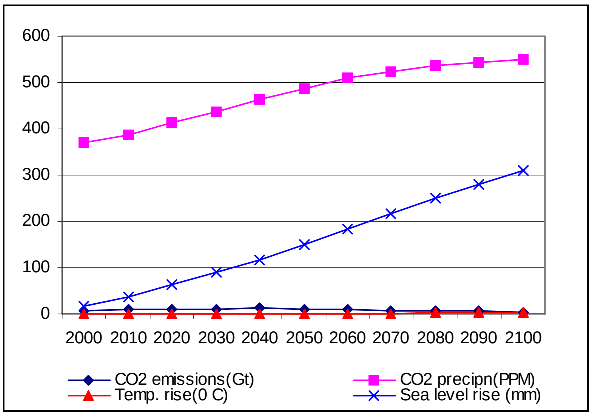
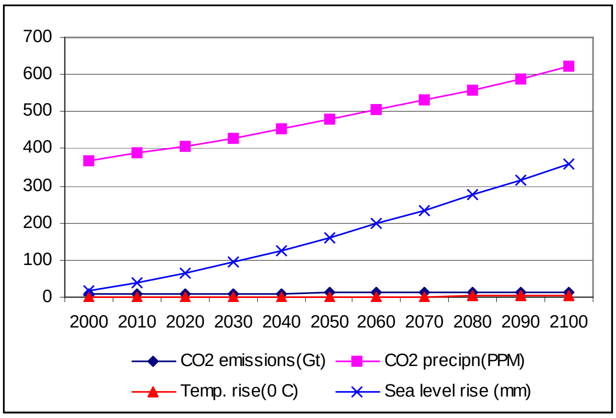


Figure 3-5: Climate indicators in B2 Scenario



Eventually, Working Group I in Third Assessment report assessed the climate implications of the CO_2 emissions as obtained in different SRES scenarios. However, since all scenario results were not available to the modellers (for their input to the Third Assessment Report) one marker scenario was chosen from each of four of the scenario groups based on the storylines (A1B, A2, B1 and B2). A set of most complex climate models, termed as coupled atmosphere-ocean general circulation models (and abbreviated as AOGCM), involved in coupling comprehensive three-dimensional atmospheric general circulation models (AGCMs), with ocean general circulation models (OGCMs), with sea-ice models, and with models of land-surface processes, are used to assess changes in precipitation, changes in net radiative heating, the increased temperature, and the direct effects of CO_2 and for inter model comparison of results. 3-2 to 3-5 depict how different climate indicators evolve in different scenarios over the time horizon 2000-2100.

In 1999, Nordhaus and Boyer used a set of equations of the simplified climatic model to link the emissions with the concentrations and eventually with the temperature increase but it does not link with seal level rise (Nordhaus and Boyer, 1999). The equations they used are as follows:

Global emissions ⇒ concentrations : simplified linear 3-reservoir model (atmosphere, biosphere+ocean surface, deep ocean)

$M_{atm}(t) = 10*ET(t) + \Phi_{11} M_{atm}(t-1) - \Phi_{12} M_{atm}(t-1) + \Phi_{21} M_{up}(t-1)$

$M_{up}(t) = \Phi_{22} M_{up}(t-1) + \Phi_{12} M_{atm}(t-1) - \Phi_{21} M_{up}(t-1) + \Phi_{32} M_{lo}(t-1) - \Phi_{23} M_{up}(t-1)$

$M_{lo}(t) = \Phi_{33} M_{lo}(t-1) - \Phi_{32} M_{lo}(t-1) + \Phi_{23} M_{up}(t-1)$

$M_{at,\,up,\,lo}(t)$ CO_2 accumulated (GtC) in atmosphere, in up layer and in low layer respectively in year t

E (t) CO_2 accumulated (GtC) in year t

Φ_{ij} transfer rate from reservoir i to j

$M_{atm}(1990) = 735$ GtC $M_{up}(1990) = 781$ GtC

$M_{lo}(1990) = 19230$ GtC $M_{atm}(0) = 590$ GtC (pre-ind)

Concentrations ⇒ Radiative forcing :

$\Delta F(t) = \gamma * \{\ln (M(t)/Mo)/\ln 2 \} + O(t)$

$\Delta F(t)$ Radiative forcing relative to pre-industrial period (W/m^2)

γ sensitivity of climate to doubling of CO_2 concentration = 4.1 W/m^2

$O(t)$ radiative forcing of other GHG's

$= - 0.1965 + 0.013465\ t$ if $t < 100$ years

$= 1.15$ if $t > 100$ years

Radiative forcing and concentration ⇒ temperature increase :

Simplified 2-reservoir model (atmosphere + ocean surface, deep ocean)

$\Delta T_{up}(t) = \Delta T_{up}(t-1) + \sigma_1 \{\Delta F(t) - \lambda\ \Delta T_{up}(t-1) - \sigma_2[\Delta T_{up}(t-1) - \Delta T_{low}(t-1)]\}$

$\Delta T_{low}(t) = \Delta T_{low}(t-1) + \sigma_3 [\Delta T_{up}(t-1) - \Delta T_{low}(t-1)]\}$

$\Delta T_{up,\ low}$ Increase in temperature of reservoir up and lo, relative to pre-ind temperature

$\sigma_{1,\ 2,\ 3}$ = thermal characteristics of reservoirs

λ = climatic feedback parameter ($=4.1 / C_s$, with C_s = sensitivity to doubling concentration = 2.9 ^0C

One period lags representing the thermal inertia of the layers

$\Delta T_{up}(1990) = 0.46\ ^0C\ \Delta T_{low}(1990) = 0.1\ ^0C$

MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change), a simple climate model[11] has been widely used by the IPCC in their various assessments. It is not a GCM, but it uses a series of reduced-form models to emulate the behaviour of fully three-dimensional, dynamic GCMs. It calculates the annual-mean global surface air temperature and global-mean sea-level implications of emissions scenarios for greenhouse gases and sulphur dioxide (Raper et al., 1996). MAGICC is a set of PC-based, user-friendly coupled computer programs designed to allow users to assess the global-mean temperature and sea level changes that might arise from future emissions of greenhouse gases and of non-greenhouse gases that affect the lifetime of methane and of sulphur dioxide. Users are able to choose which emissions scenarios to use, or to define their own, and also to alter a number of model parameters to explore uncertainty. MAGICC is available for use on a restricted circulation basis, usually for a small handling charge and only under licence to the Climatic Research Unit.

3.1.2. Energy related indicators

Three indicators are considered in this category, 1) energy system costs, 2) energy costs to the consumer and 3) security of energy supply. Energy system costs are the output of a typical energy system model. Energy costs to the consumer can be represented by the energy system costs. The third indicator, security of energy supply can be measured in two ways, a) import dependence in a particular year, and b) depletion of resources or resources left at a particular year.

Import dependence is applicable for a country or region. Excessive import dependence possesses threat in terms of energy supply security of a region or country. Import dependence is measured as percentage share of import in the total supply. It can be applicable for a fuel, particularly fossil one as well for the total primary energy. A typical energy system model calculates both the import and primary energy supply and therefore, import dependence can be calculated easily.

---

[11] Simplifications can be made so that the climate model has reduced complexity (e.g., a reduction in dimensionality to two or even zero). Simple models allow one to explore the potential sensitivity of the climate to a particular process over a wide range of parameters.

Another indicator for measuring energy security which is applicable even at the global level, is the depletion of resources or resources left at a certain point of time. Traditionally energy resource[12] assessments have focussed on the immediate to short term accessibility of oil, gas and coal reserves[13] usually in terms of annual reserve additions relative to current production. Reserves data on fossil fuels are assessed by several organisations annually and brought out regularly by World Energy Council, OPEC, EIA, BP etc for the current year. Tables A2.1 to A2.3 in Annex 2, present the reserves data for coal, oil and natural gas as of 1999 available from different sources.

The most commonly used measure of resource depletion is the reserve-production ratios, which is obtained by dividing the reserves in a particular year with the production and represents remaining life of reserves in terms of years at the rate of current production. However, the concept of reserve to production ratios is seriously flawed and in the past has led to aberrant conclusions (Rogner, 1997). For oil, ratios ranging from 20 to 40 years have existed since the beginning of the twentieth century, so the world should have run out of oil a long time ago (Table 3-2).

Table 3-2 Reserve –production ratio for oil

Year	Reserves	Production	Reserve-production ratio (year)
1950	10,600	521	20
1955	21,600	771	36
1960	41,000	1085	38
1965	47,600	1547	31
1970	77,908	2336	33
1975	88,822	2708	33
1980	88,292	3086	29
1985	95,471	2737	35
1990	136,800	3149	42
1997	151,409	3495	43

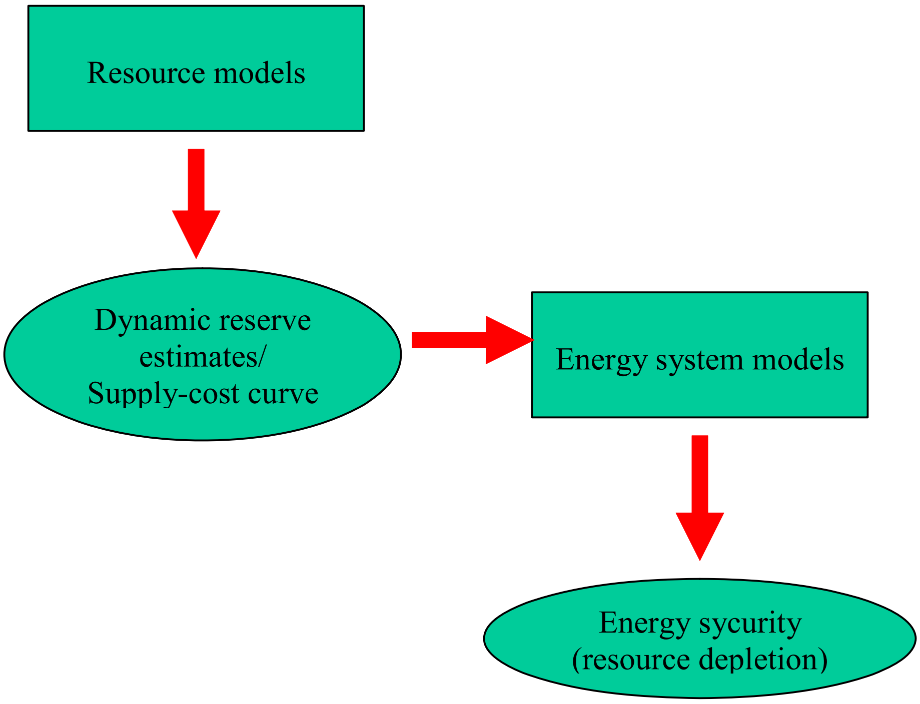
In reality, the concept of reserves is dynamic. Driven by economics, advances in the geosciences and technological progress in the upstream production operations, reserves have been continuously replenished from previously unknown (newly discovered) or techno-economically in accessible occurrences (Rogner 1997).

---

[12] Resources are defined as ``concentrations of naturally occurring solid, liquid or gaseous materials in or on the Earth's crust in such form that economic extraction of a commodity from the concentration is currently or potentially feasible (US Bureau of Mines and US Geological Survey, 1980). Along the geological dimension, they are divided into identified and undiscovered resources. Identified resources are those whose location, grade, quality and quantity are known or estimated from specific geological evidence. Unconventional resources are those materials that are low grade and not considered as potentially economic.

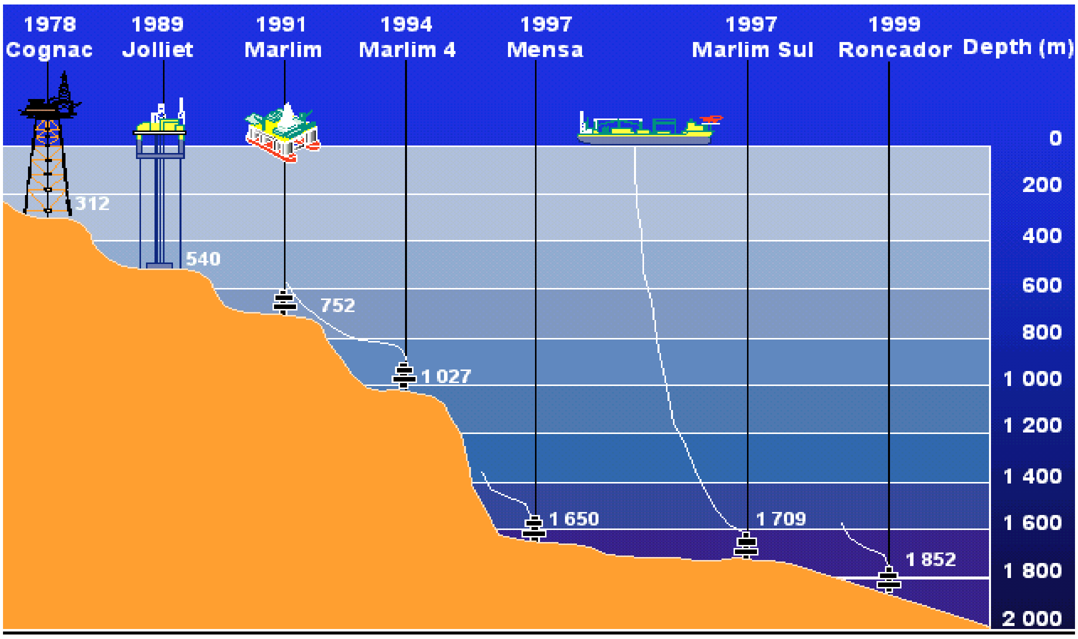
[13] Reserves are generally defined as that part of an identified resource which can be technically and economically extracted at the time of determination. Thus reserve estimates inherently depend on the state – of-the art of present exploration and production technologies as well as on the prevailing and anticipated market prices.

Figure 3-6: Modelling linkage for energy security



In general, energy system models address a longer time horizon of 30 to 50 years or even beyond, and therefore, the application of reserve and resource volumes based on the static concept of present technology and cost regimes is insufficient. In an analysis that covers half a century or even more needs resource assessments and recoverability evaluations that extend far beyond conventional reserve analysis and reserve to production ratio. The nature of this study calls for a dynamic resource assessment.

Figure 3-7 Deep Offshore Production Records *(Source IFP)*



Therefore, analysis of resource depletion is far from simple. Ideally it needs a resource model link with the energy system model. Figure 3-6 presents the modelling linkage required to analyse the energy security in terms of resource depletion.

Resource model will provide an availability assessments of the energy resources in the form of supply-cost functions in which discrete reserve/resource quantities are cumulatively arranged in an increasing order of cost of extraction (SAUNER, 2000). Supply-cost curves show what quantities of a mineral commodity can be supplied at a given price or what price level will be required to meet a given demand.

Reserve/resource quantities and related supply-cost curves are subject to continuous change over time for several reasons. Production inevitably depletes reserves and eventually leads to exhaustion of deposit, while successful exploration add new reserves and resources (SAUNER, 2000). Price increases and cost reduction measures expand reserves by moving resources into the reserve category. The most important force in this process is technology. Technological improvements are continuously pushing resources into the reserve category through lowering cost of extraction. For instance, it is now both feasible and profitable to exploit oil fields at water depths exceeding 1 000 metres, which was still thought to be impossible 15 years ago. Figure 7 presents the technological evolution in exploitation of deep water oil resources. In 1978, the greatest production depth was 300 m. By 1998, deepwater production was under way at 1 800 m. For oil companies, the next target depth is 3 000 m (WEC, 2001).

Therefore, the technological progress and effects of time have to be taken into consideration in the process of long-range reserve/resource estimations. To account the exploration success in the next century, estimates of undiscovered resources have to be included in the inventory. This can be done by estimating the cost-reducing effects of technological improvements and by including unconventional resources.

Rogner in 1997, estimated the hydrocarbon reserves taking into account the vast unconventional hydrocarbon occurrences and their mobilisation with historically observed rates of technology change (Rogner, 1997). He considered both conventional and unconventional occurrences for oil and natural gas. Conventional occurrences are "those that can be exploited with current technology and present market conditions". Unconventional occurrences "cannot be tapped with conventional production methods, because of technical or economic reasons or both". He estimated the resource quantity –cost relations also. However, time dimension was taken out from the estimation. This means he developed a single aggregate resource cost curve per resource and region.

Later in 2000, SAUNER project reassessed the supply –cost functions for fossil sources taking into account the time dimension. These cost functions are determined for 25-year intervals between 2000 and 2100. Figures 8 to 10 present them for the world as a whole. They are available for different regions of the world as well. Costs are at 1998 US$. However, many assumptions have been made to assess the resource availability extending over a period of 100 years. This pertains also to the cost of extraction of the outer segments of the

Figure 3-8 World crude oil supply-cost curve (Base case)

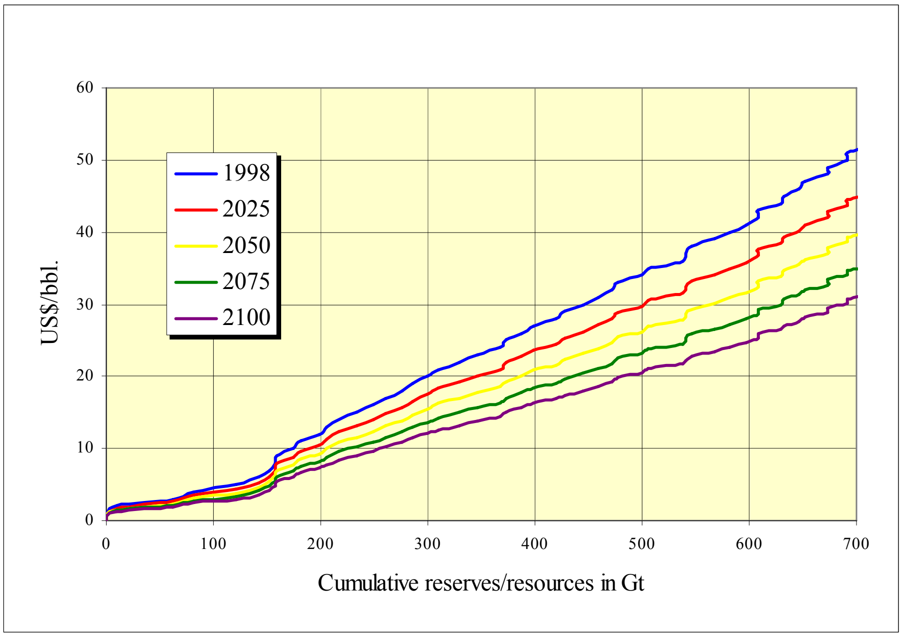


Figure 3-9: World natural gas supply-cost curve (Base case)

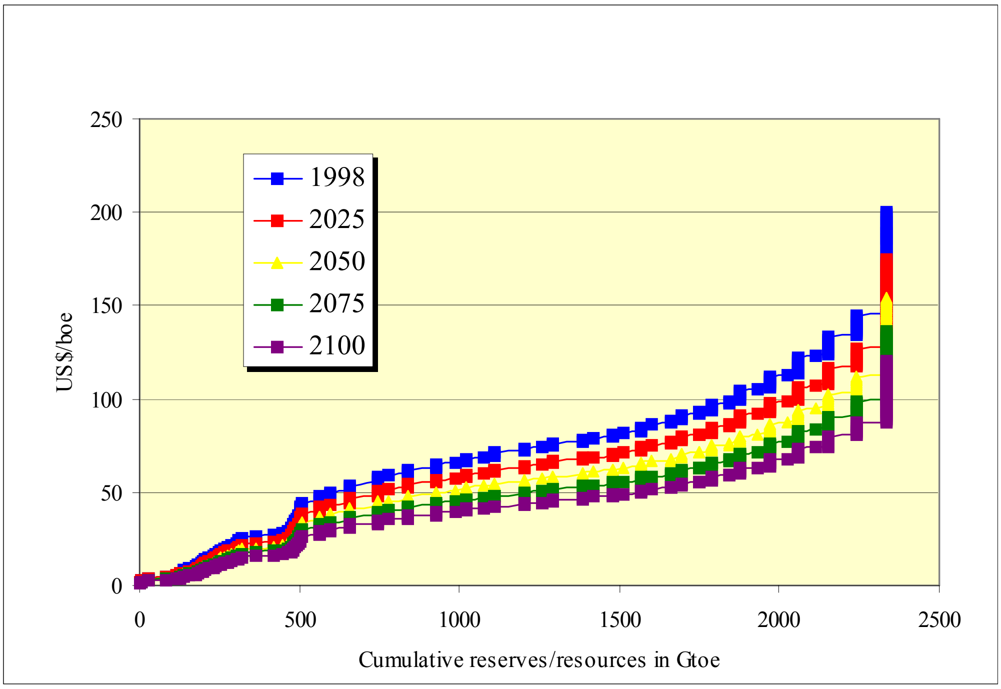
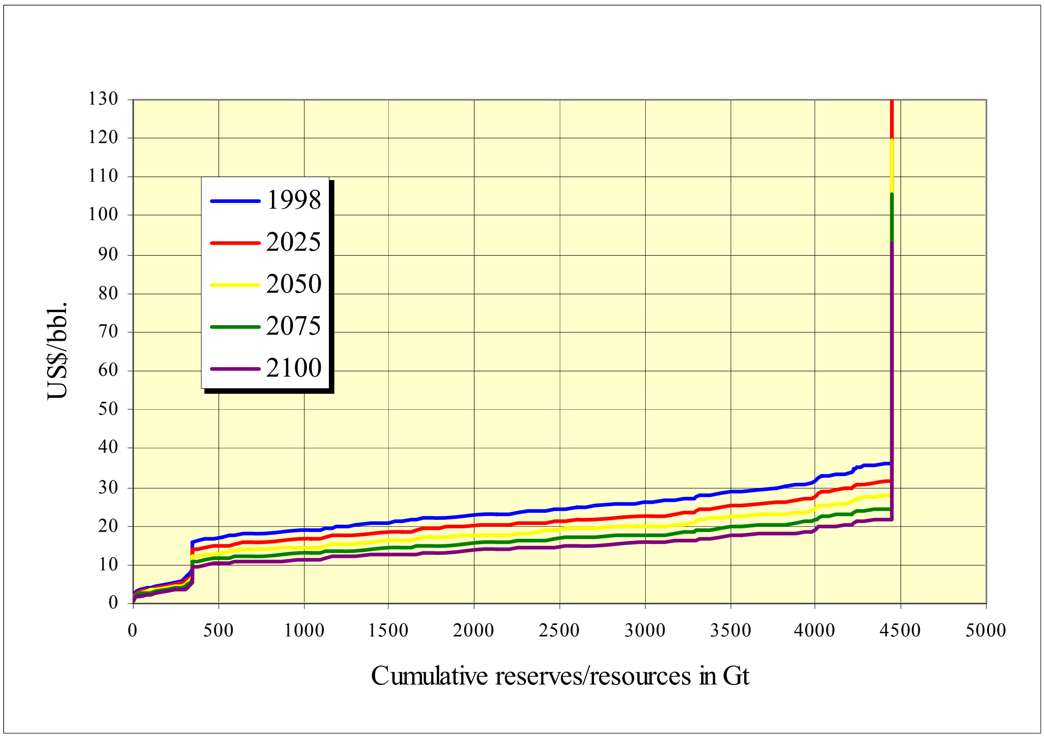


Figure 3-10 World coal supply-cost curve (Base case)

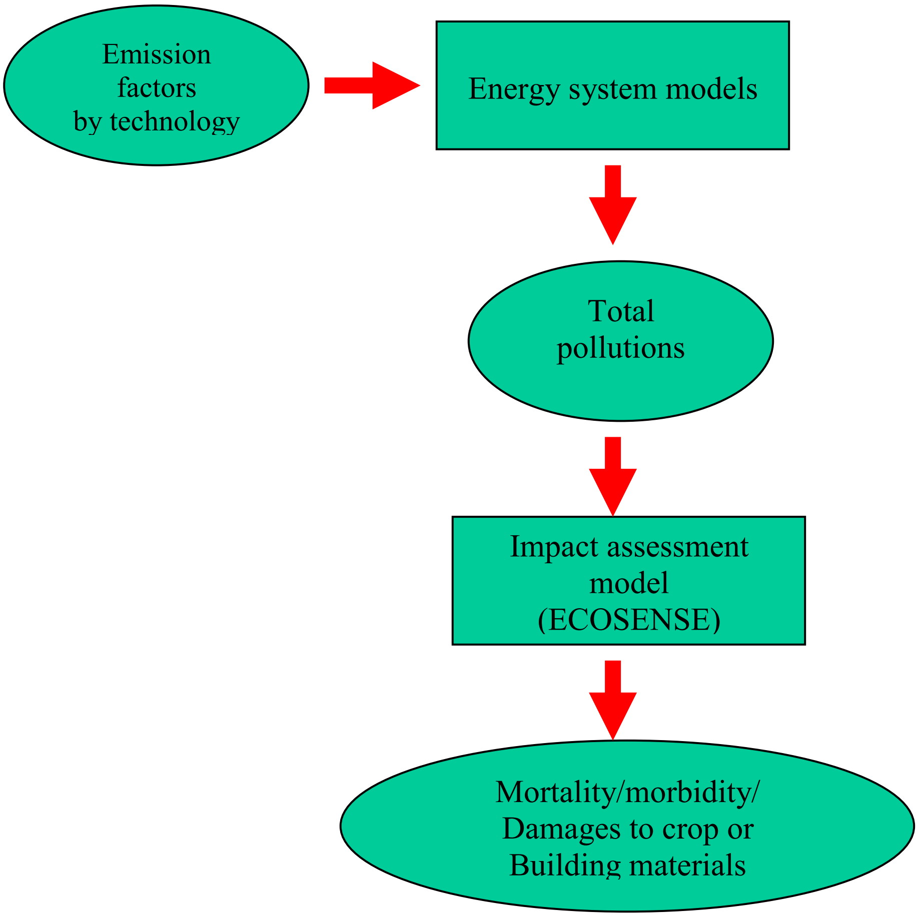


conventional resources and to unconventional resources currently not produced in significant amounts. Therefore, these estimations are to be accepted with caveats. More specifically, they present at best a first approximation of the order of magnitude of the resource supply path over time (SAUNER, 2000).To avoid a development of resource model link with the energy system models, these supply –cost curves can be used in the energy system models. For demand driven model, based on these supply curves, the energy model will determine the production level for a mile stone year and hence resource left can be calculated for that year. For those energy models with MACRO link, the supply curves may lead the models to adjust the demand and an optimal production level will be reached from which the remaining resource can be estimated.

3.1.3. Health and air pollution

Three indicators are considered in this category, 1) mortality changes, 2) morbidity changes and 3) monetary damages caused by the air pollution. Figure 11 presents the modelling linkage for the indicators. Technology specific emissions factor will estimate the total pollutions of different pollutants. Then an impact assessment model, ECOSENSE for example, can be used to estimate the above-mentioned indicators. However, in absence of a direct interface between two models, perhaps the data on damages per tonne of pollutant as estimated by ECOSENSE can be used to estimate the total damages.

Figure 3-11 Modelling linkages for measuring pollution related damages



We first discuss the emissions factors followed by the data on pollution related damages as obtained from ECOSENSE.

(a) Emissions factors

We provide the emissions factors for power generation and transport technologies.

Power

Table A2.4 in Annex 2 presents the emissions factor for power generation technologies. Data are obtained from the IKARAUS project and a study undertaken for Ankett Commission. Emissions factors are provided for fossil and nuclear technologies. Data sets are dynamic covering the period 2000-30. Also, data are available for a number of new fossil technologies like IGCC, CO_2 disposal etc.

Transport

Emissions standards are numerical limits set by a governing body or agency to regulate the amount of key air pollutants (e.g., NOx, HC, CO) that are emitted through the tailpipe or leak out of the engine. The tailpipe emission standards[14] were initiated in California in 1959 to control CO and HC emissions from gasoline engines. Today, emissions from internal combustion engines are regulated in tens of countries throughout the world. Tailpipe emission standards are usually implemented by government ministries responsible for the protection of environment, such as the EPA (Environmental Protection Agency) in the USA. The duty to comply with these standards is on the equipment (engine) manufacturer. Typically all equipments have to be emission certified before it is released to the market. Emissions standards in some of the countries are discussed in the following sections:

USA

Heavy duty vehicles

The following emission standards apply to new diesel engines used in heavy-duty highway vehicles. Heavy-duty vehicles are defined as vehicles of GVWR (gross vehicle weight rating) of above 8,500 lbs in the federal jurisdiction.

Model Year 1987-2003

Model year 1988-2003 US federal (EPA) emission standards for heavy-duty diesel truck and bus engines are summarized in the following tables. Applicable to the 1994 and following year standards, sulfur content in the certification fuel has been reduced to 500 ppm wt.

Table 3-3: EPA Emission Standards for Heavy-Duty Diesel Engines, g/bhp•hr

Year	HC	CO	NO_x	PM
Heavy-Duty Diesel Truck Engines				
1988	1.3	15.5	10.7	0.60
1990	1.3	15.5	6.0	0.60
1991	1.3	15.5	5.0	0.25
1994	1.3	15.5	5.0	0.10
1998	1.3	15.5	4.0	0.10
Urban Bus Engines				
1991	1.3	15.5	5.0	0.25
1993	1.3	15.5	5.0	0.10
1994	1.3	15.5	5.0	0.07
1996	1.3	15.5	5.0	0.05*
1998	1.3	15.5	4.0	0.05*

- - in-use PM standard 0.07

Table 3-4 shows a voluntary Clean Fuel Fleet (CFF) emission standard. It is a federal standard that applies to 1998-2003 model year engines, over 8,500 lbs GVWR. In addition to the CFF standard, vehicles must meet applicable conventional standards for other pollutants.

Table 3-4 Clean Fuel Fleet Program for Heavy-Duty SI and CI Engines, g/bhp•hr

Category*	CO	$NMHC+NO_x$	PM	HCHO
LEV (Federal Fuel)		3.8		
LEV (California Fuel)		3.5		
ILEV	14.4	2.5		0.050
ULEV	7.2	2.5	0.05	0.025
ZLEV	0	0	0	0

* LEV - low emission vehicle; ILEV - inherently low emission vehicle; ULEV - ultra low emission vehicle; ZEV - zero emission vehicle

---

[14] Tailpipe" emission standards specify the maximum amount of pollutants allowed in exhaust gases discharged from a diesel engine.

Model Year 2004 and Later

In October 1997, EPA adopted new emission standards for model year 2004 and later heavy-duty diesel truck and bus engines. The goal was to reduce NOx emissions from highway heavy-duty engines to levels approximately 2.0 g/bhp•hr beginning in 2004. Manufacturers have the flexibility to certify their engines to one of the two options shown in Table 3-5.

Table 3-5 EPA Emission Standards for MY 2004 and Later HD Diesel Engines, g/bhp•hr

Option	NMHC + NO_x	NMHC
1	2.4	n/a
2	2.5	0.5

All emission standards other than NMHC and NOx applying to 1998 and later model year heavy duty engines (Table 3-5) will continue at their 1998 levels.

Model Year 2007 and Later

On December 21, 2000 the EPA signed emission standards for model year 2007 and later heavy-duty highway engines (the California ARB adopted virtually identical 2007 heavy-duty engine standards in October 2001). The rule includes two components: (1) emission standards, and (2) diesel fuel regulation. The first component of the regulation introduces new, very stringent emission standards, as follows:

PM - 0.01 g/bhp-hr

NOx - 0.20 g/bhp-hr

NMHC - 0.14 g/bhp-hr

The PM emission standard will take full effect in the 2007 heavy-duty engine model year. The NOx and NMHC standards will be phased in for diesel engines between 2007 and 2010. The phase-in would be on a percent-of-sales basis: 50% from 2007 to 2009 and 100% in 2010 (gasoline engines are subject to these standards based on a phase-in requiring 50% compliance in 2008 and 100% compliance in 2009).

The diesel fuel regulation limits the sulfur content in on-highway diesel fuel to 15 ppm (wt.), down from the previous 500 ppm. Refiners will be required to start producing the 15 ppm S fuel beginning June 1, 2006. At the terminal level, highway diesel fuel sold as low sulfur fuel must meet the 15 ppm sulfur standard as of July 15, 2006. For retail stations and wholesale purchasers, highway diesel fuel sold as low sulfur fuel must meet the 15 ppm sulfur standard by September 1, 2006.

Light duty vehicles

Two sets of standards, Tier 1 and Tier 2, have been defined for light-duty vehicles in the Clean Air Act Amendments (CAAA) of 1990. The Tier 1 regulations were published as a final rule on June 5, 1991 and fully implemented in 1997. The Tier 2 standards were adopted on December 21, 1999, to be phased-in beginning in 2004.

Tier 1 Standards

Tier 1 light-duty standards apply to all new light duty vehicles (LDV), such as passenger cars, light duty trucks, sport utility vehicles (SUV), minivans and pick-up trucks. The LDV category includes all vehicles of less than 8500 lb gross vehicle weight rating, or GVWR (i.e., vehicle weight plus rated cargo capacity).

The Tier 1 standards were phased-in progressively between 1994 and 1997. They apply to a full vehicle useful life of 100,000 miles (effective 1996). The regulation also defines an intermediate standard to be met over a 50,000 miles period. The difference between diesel and gasoline car standards is a more relaxed NOx limit for diesels, which applies to vehicles through 2003 model year.

Tier 2 Standards

The Tier 2 standards bring significant emission reductions relative to the Tier 1 regulation. Under the Tier 2 standard, the same emission standards apply to all vehicle weight categories, i.e., cars, minivans, light duty trucks, and SUVs have the same emission limit. Since light-duty emission standards are expressed in grams of pollutants per mile, large engines (such as those used in light trucks or SUVs) will have to utilize more advanced emission control technologies than smaller engines in order to meet the standard.

In Tier 2, the applicability of light-duty emission standards has been extended to cover some of the heavier vehicle catagories. The Tier 1 standards applied to vehicles up to 8500 lbs GWVR. The Tier 2 standard applies to all vehicles that were covered by Tier 1 and, additionally, to "medium-duty passenger vehicles" (MDPV). The MDPV is a new class of vehicles that are rated between 8,500 and 10,000 GVWR and are used for personal transportation. The same emission limits apply to all engines regardless of the fuel they use. That is, vehicles fueled by gasoline, diesel, or alternative fuels all must meet the same standards.

<u>Table 3-6 EPA Tier 1 Emission Standards for Passenger Cars and Light-Duty Trucks, FTP 75, g/mi</u>

Category	**50,000 miles/5 years**						**100,000 miles/10 years**[1]					
	THC	**NMHC**	**CO**	**NOx diesel**	***NOx gasoline***	**PM**	**THC**	**NMHC**	**CO**	**NOx diesel**	***NOx gasoline***	**PM**
Passenger cars	0.41	0.25	3.4	1.0	*0.4*	0.08	-	0.31	4.2	1.25	*0.6*	0.10
LLDT, LVW <3,750 lbs	-	0.25	3.4	1.0	*0.4*	0.08	0.80	0.31	4.2	1.25	*0.6*	0.10
LLDT, LVW >3,750 lbs	-	0.32	4.4	-	*0.7*	0.08	0.80	0.40	5.5	0.97	*0.97*	0.10
HLDT, ALVW <5,750 lbs	0.32	-	4.4	-	*0.7*	-	0.80	0.46	6.4	0.98	*0.98*	0.10
HLDT, ALVW >5,750 lbs	0.39	-	5.0	-	*1.1*	-	0.80	0.56	7.3	1.53	*1.53*	0.12

1 - Useful life 120,000 miles/11 years for all HLDT standards and for THC standards for LDT

Abbreviations:
LVW - loaded vehicle weight (curb weight + 300 lbs)
ALVW - adjusted LVW (the numerical average of the curb weight and the GVWR)
LLDT - light light-duty truck (below 6,000 lbs GVWR)
HLDT - heavy light-duty truck (above 6,000 lbs GVWR)

The Tier 2 tailpipe standards are structured into 8 certification levels of different stringency, called "certification bins", and an average fleet standard for NOx emissions. Vehicle manufacturers will have a choice to certify particular vehicles to any of the 8 bins. At the same time, the average NOx emissions of the entire vehicle fleet sold by each manufacturer will have to meet the average NOx standard of 0.07 g/mi. Additional temporary certification bins (bin 9, 10, and an MDPV bin) of more relaxed emisison limits will be available in the transition period. These bins will expire after 2008 model year.

The Tier 2 standards will be phased-in between 2004 and 2009. For new passenger cars and light LDTs, Tier 2 standards will phase in beginning in 2004, with the standards to be fully phased in by 2007. For heavy LDTs and MDPVs, the Tier 2 standards will be phased in beginning in 2008, with full compliance in 2009. During the phase-in period from 2004-2007, all passenger cars and light LDTs not certified to the primary Tier 2 standards will have to meet an interim average standard of 0.30 g/mi NOx, equivalent to the current NLEV standards for LDVs. During the period 2004-2008, heavy LDTs and MDPVs not certified to the final Tier 2 standards will phase in to an interim program with an average standard of 0.20 g/mi NOx, with those not covered by the phase-in meeting a per-vehicle standard (i.e., an emissions "cap") of 0.60 g/mi NOx (for HLDTs) and 0.90 g/mi NOx (for MDPVs). The emission standards for all pollutants (certification bins) are shown in the following table.

Table 3-7 Tier 2 Emission Standards, FTP 75, g/mi

Bin#	**50,000 miles**					**120,000 miles**				
	NMOG	**CO**	**NOx**	**PM**	**HCHO**	**NMOG**	**CO**	**NOx***	**PM**	**HCHO**
Temporary Bins										
MDPV[c]						0.280	7.3	0.9	0.12	0.032
10[a,b,d,f]	0.125 (0.160)	3.4 (4.4)	0.4	-	0.015 (0.018)	0.156 (0.230)	4.2 (6.4)	0.6	0.08	0.018 (0.027)
9[a,b,e]	0.075 (0.140)	3.4	0.2	-	0.015	0.090 (0.180)	4.2	0.3	0.06	0.018
Permanent Bins										
8[b]	0.100 (0.125)	3.4	0.14	-	0.015	0.125 (0.156)	4.2	0.20	0.02	0.018
7	0.075	3.4	0.11	-	0.015	0.090	4.2	0.15	0.02	0.018
6	0.075	3.4	0.08	-	0.015	0.090	4.2	0.10	0.01	0.018
5	0.075	3.4	0.05	-	0.015	0.090	4.2	0.07	0.01	0.018
4	-	-	-	-	-	0.070	2.1	0.04	0.01	0.011
3	-	-	-	-	-	0.055	2.1	0.03	0.01	0.011
2	-	-	-	-	-	0.010	2.1	0.02	0.01	0.004
1	-	-	-	-	-	0.000	0.0	0.00	0.00	0.000

* - average manufacturer fleet NOx standard is 0.07 g/mi

a - Bin deleted at end of 2006 model year (2008 for HLDTs)
b - The higher temporary NMOG, CO and HCHO values apply only to HLDTs and expire after 2008
c - An additional temporary bin restricted to MDPVs, expires after model year 2008
d - Optional temporary NMOG standard of 0.195 g/mi (50,000) and 0.280 g/mi (120,000) applies for qualifying LDT4s and MDPVs only
e - Optional temporary NMOG standard of 0.100 g/mi (50,000) and 0.130 g/mi (120,000) applies for qualifying LDT2s only
f - 50,000 mile standard optional for diesels certified to bin 10

The Tier 2 regulation brings new requirements for fuel quality. Cleaner fuels will be required by advanced emission aftertreatment devices (e.g. catalysts) that are needed to meet the regulations.

Sulfur Levels in Gasoline -- The program requires that most refiners and importers meet a corporate average gasoline sulfur standard of 120 ppm and a cap of 300 ppm beginning in 2004. By 2006, the average standard will be reduced to 30 ppm with 80 ppm sulfur cap. Temporary, less stringent standards will apply to some small refiners through 2007. In addition, temporary, less stringent standards will apply to a limited geographic area in the western U.S. for the 2004-2006 period.

Diesel Fuel Quality -- In May, 1999, the EPA published and Advanced Notice of Proposed Rulemaking (ANPRM) on the quality of diesel fuel, soliciting comments on what sulfur levels are needed and when. Proposed rulemaking on diesel fuel sulfur is expected in early 2000.

European Union

All Member States within the European Union (EU) observe the same emission standards from internal combustion engines as set by the Union.

Regulated Types of Diesel Engines

Currently the following categories of new diesel engines and/or vehicles are subject to emission standards in the EU:

Heavy-Duty Truck and Bus Engines
Cars and Light Trucks
Off-Road Diesel Engines

The European regulations for new heavy-duty diesel engines are commonly referred to as Euro I ... V. The Euro I standards for medium and heavy-duty engines were introduced in 1992. The Euro II regulations came to power in 1996. These standards applied to both heavy-duty highway diesel engines and urban buses. The urban bus standards, however were voluntary.

In 1999, the European Parliament and the Council of Environment Ministers adopted the final Euro III standard and also adopted Euro IV and V standards for the year 2005/2008. The standards also set specific, stricter values for extra low emission vehicles (also known as "enhanced environmentally friendly vehicles" or EEVs) in view of their contribution to reducing atmospheric pollution in cities.

In April 2001, the European Commission adopted *Directive 2001/27/EC* which introduced further amendments to Directive 88/77/EEC. The following table contains a summary of the emission standards and their implementation dates.

Table 3-8 EU Emission Standards for HD Diesel Engines, g/kWh (smoke in m^{-1})

Tier	Date & Category	Test Cycle	CO	HC	NOx	PM	Smoke
Euro I	1992, <85 kW	ECE R-49	4.5	1.1	8.0	0.612	
	1992, >85 kW		4.5	1.1	8.0	0.36	
Euro II	1996.10		4.0	1.1	7.0	0.25	
	1998.10		4.0	1.1	7.0	0.15	
Euro III	*1999.10, EEVs only*	*ESC* & *ELR*	*1.5*	*0.25*	*2.0*	*0.02*	*0.15*
	2000.10	ESC & ELR	2.1	0.66	5.0	0.10 0.13*	0.8
Euro IV	2005.10		1.5	0.46	3.5	0.02	0.5
Euro V	2008.10		1.5	0.46	2.0	0.02	0.5

* - for engines of less than 0.75 dm^3 swept volume per cylinder and a rated power speed of more than 3000 min^{-1}

Emission standards for diesel engines that are tested on the ETC test cycle, as well as for heavy-duty gas engines, are summarized in the following table.

Table 3-9 Emission Standards for Diesel and Gas Engines, ETC Test, g/kWh

Tier	Date & Category	Test Cycle	CO	NMHC	CH_4[a]	NOx	PM[b]
Euro III	*1999.10, EEVs only*	*ETC*	*3.0*	*0.40*	*0.65*	*2.0*	*0.02*
	2000.10	ETC	5.45	0.78	1.6	5.0	0.16 0.21[c]
Euro IV	2005.10		4.0	0.55	1.1	3.5	0.03
Euro V	2008.10		4.0	0.55	1.1	2.0	0.03

a - for natural gas engines only
b - not applicable for gas fueled engines at the year 2000 and 2005 stages
c - for engines of less than 0.75 dm^3 swept volume per cylinder and a rated power speed of more than 3000 min^{-1}

Japan

Japan introduced fist engine emissions standards in the late 1980's, however, it remained relaxed through the 1990's. In March 2003 the Ministry of the Environment finalized very stringent 2005 emission standards for both light and heavy vehicles. At the time they come to power, the 2005 heavy-duty emission standards will be the most stringent diesel emission regulation in the world. Two types of standards are usually established, denoted as "mean" and "max" (the "max" standards are shown in brackets in the following tables). The "mean" standards are to be met as a type approval limit and as a production average. The "max" standards are to be met generally as an individual limit in series production and as type approval limit if sales are less than 2000 per vehicle model per year.

Passenger Cars

Emission standards for new diesel powered cars are listed in the following table.

Table 3-10 Japanese Emission Standards for Diesel Passenger Cars, g/km

Vehicle Weight	**Date**	**Test**	**CO**	**HC**	**Nox**	**PM**
			mean (max)	mean (max)	mean (max)	mean (max)
< 1250 kg*	1986	10-15 mode	2.1 (2.7)	0.40 (0.62)	0.70 (0.98)	
	1990		2.1 (2.7)	0.40 (0.62)	0.50 (0.72)	
	1994		2.1 (2.7)	0.40 (0.62)	0.50 (0.72)	0.20 (0.34)
	1997		2.1 (2.7)	0.40 (0.62)	0.40 (0.55)	0.08 (0.14)
	2002[a]		0.63	0.12	0.28	0.052
	2005[b]	New mode[c]	0.63	0.024[d]	0.14	0.013
> 1250 kg*	1986	10-15 mode	2.1 (2.7)	0.40 (0.62)	0.90 (1.26)	
	1992		2.1 (2.7)	0.40 (0.62)	0.60 (0.84)	
	1994		2.1 (2.7)	0.40 (0.62)	0.60 (0.84)	0.20 (0.34)
	1998		2.1 (2.7)	0.40 (0.62)	0.40 (0.55)	0.08 (0.14)
	2002[a]		0.63	0.12	0.30	0.056
	2005[b]	New mode[c]	0.63	0.024[d]	0.15	0.014

* - equivalent inertia weight (EIW); vehicle weight of 1265 kg
a - 2002.10 for domestic cars, 2004.09 for imports
b - full implementation by the end of 2005
c - full phase-in by 2011
d - non-methane hydrocarbons

Commercial Vehicles

Emission standards for new diesel fueled commercial vehicles are summarized in Table 3-11 for light vehicles and in Table 3-3 for heavy vehicles.

Table 3-11 Diesel Emission Standards for Light Commercial Vehicles *GVW ≤ 2500 kg (≤ 3500 kg beginning 2005)*

Vehicle Weight*	**Date**	**Test**	**Unit**	**CO**	**HC**	**NOx**	**PM**
				mean (max)	mean (max)	mean (max)	mean (max)
? 1700 kg	1988	10-15 mode	g/km	2.1 (2.7)	0.40 (0.62)	0.90 (1.26)	
	1993			2.1 (2.7)	0.40 (0.62)	0.60 (0.84)	0.20 (0.34)
	1997			2.1 (2.7)	0.40 (0.62)	0.40 (0.55)	0.08 (0.14)
	2002			0.63	0.12	0.28	0.052
	2005[b]	New mode[c]		0.63	0.024[d]	0.14	0.013
> 1700 kg	1988	6 mode	ppm	790 (980)	510 (670)	DI: 380 (500) IDI: 260 (350)	
	1993	10-15 mode	g/km	2.1 (2.7)	0.40 (0.62)	1.30 (1.82)	0.25 (0.43)
	1997[a]			2.1 (2.7)	0.40 (0.62)	0.70 (0.97)	0.09 (0.18)
	2003			0.63	0.12	0.49	0.06
	2005[b]	New mode[c]		0.63	0.024[d]	0.25	0.015

* - gross vehicle weight (GVW)
a - 1997: manual transmission vehicles; 1998: automatic transmission vehicles
b - full implementation by the end of 2005
c - full phase-in by 2011
d - non-methane hydrocarbons

***Table 3-12 Diesel Emission Standards for Heavy Commercial Vehicles** GVW > 2500 kg (> 3500 kg beginning 2005)*

Date	**Test**	**Unit**	**CO** mean (max)	**HC** mean (max)	**NOx** mean (max)	**PM** mean (max)
1988/89	6 mode	ppm	790 (980)	510 (670)	DI: 400 (520) IDI: 260 (350)	
1994	13 mode	g/kWh	7.40 (9.20)	2.90 (3.80)	DI: 6.00 (7.80) IDI: 5.00 (6.80)	0.70 (0.96)
1997[a]			7.40 (9.20)	2.90 (3.80)	4.50 (5.80)	0.25 (0.49)
2003[b]			2.22	0.87	3.38	0.18
2005[c]	JE05		2.22	0.17[d]	2.0	0.027

a - 1997: GVW ? 3500 kg; 1998: 3500 < GVW ? 12000 kg; 1999: GVW > 12000 kg
b - 2003: GVW ? 12000 kg; 2004: GVW > 12000 kg
c - full implementation by the end of 2005
d - non-methane hydrocarbons

Argentina

Trucks and Buses

The standards are based on European regulations for heavy-duty vehicles. Emission standards for new diesel trucks, buses, and light commercial vehicles (LCV) in Argentina are summarized in Table 13.

Table 3-13 Emission Standards for Diesel Trucks and Buses

Year	**Category**	**Reference Standard**	**CO** g/kWh	**HC**	**NOx**	**PM**
1994	Urban buses	Euro 0	11.2	2.45	14.4	-
1995	Urban buses	Euro I*	4.9	1.23	9.0	-
1996	LCV / Trucks	Euro I*	4.9	1.23	9.0	0.4[a]
1998	Urban buses	Euro II	4.0	1.1	7.0	0.4[a]
2000	LCV / Trucks	Euro II	4.0	1.1	7.0	0.15[a]

a - multiply by a factor of 1.7 for engines below 85 kW
* - production conformity limit

Table 3-14 Emission Standards for Diesel Cars

Year	**CO** g/km	**HC**	**NOx**	**PM**
1994	24.0	2.1	2.0	-
1996	12.0	1.2	1.4	0.373
1998	6.2	0.5	1.43	0.16*
2000	2.0	0.3	0.6	0.124

* - 0.31 g/km for vehicles above 1700 kg

Emissions factor

The main source of emissions from road vehicles are the exhaust gases and hydrocarbons produced by evaporation of fuels. Emissions factors consist of three components.

$$E = E_{\text{cold start}} + E_{\text{hot}} + E_{\text{evaporative}} \qquad (1)$$

Where, E is the total emissions.

When an engine is started below its normal operating temperature, it uses fuel inefficiently, and the amount of pollution ($E_{\text{cold start}}$) produced is higher than when it is hot. Hot emissions (E_{hot}) are the emissions produced when the engine and the pollution control systems of the vehicle (e.g catalyst) have reached their normal operating temperature. Evaporative emissions ($E_{\text{evaporative}}$) occur in a number of different ways. Fuel vapour is expelled from the tank each time it is refilled, the daily increase in temperature (compared with overnight temperatures) causes fuel vapour to expand and be released from the fuel tank, and vapour is created wherever fuel may be released to the air, especially when the vehicle is hot during or after use. Emissions factors depend upon a number of factors, vehicle speed, driving cycle, road type (urban, rural or highway) and road conditions are some of them. We provide the average emissions factor for existing and future vehicle technologies.

Under MEET project all three types of emissions factors are estimated for European countries. Cold start emissions factors are calculated for 4 pollutants CO, CO_2, HC and NOx for gasoline and diesel cars present and near future till EURO IV standard vehicles. Other parameters considered are technology (diesel, catalyst, and conventional cars), average speed, ambient temperature, seasons and travelled distance. These emissions factors can be obtained from the report prepared by INRETS (INRETS, 1999).

Evaporative emissions factor for average conventional vehicles in Europe is estimated as 0.98 g/km and 0.03 g/km for the catalyst vehicles. Average aggregated factor is 0.6 g/km for Europe.

Near future vehicles

MEET project estimated the emissions factors for near furure vehicles (EURO III and IV). The emission data sets used to derive hot emission factors and cold start excess emissions are based on vehicles upto model year 1994. The derivation of reduction rates for future vehicle technologies is based on the exhaust legislation of the EU. In order to comply with the standards the automobile manufacturers have the possibilities to reduce the hot emission level in the stabilised phase of the test and the cold start emissions. For future vehicle technologies therefore the intention is to assess reduction rates both for hot emissions and cold start excess emissions taking into account abatement concepts which will probably introduced.

Taking into account the proposed EC Directive (EC, 1996) for future emissions standards reduction rates for the future steps relative to EURO 1 vehicles, emissions levels of vehicle categories Euro 2 to 4 are calculated. Tables 15 and 19 present the emissions factors for EURO I gasoline and diesel LDVs. Tables 16 and 20 present the reduction rates over EURO I. Tables 17 and 18 present the emissions factors for EURO III and IV gasoline vehicles, while Tables 21 to 24 present the same for EURO II to EURO IV vehicles.

Table 3-15 Emissions levels and cold start excess emissions of Euro 1 gasoline vehicles (g/km)

Driving cycle	CO	HC	Nox
UDC-cold	4.05	0.57	0.43
UDC-hot	0.96	0.1	0.19
EUDC	0.66	0.06	0.23
NEDC-cold	1.9	0.24	0.3
NEDC-hot	0.77	0.07	0.22
Cold start excess emission*	12.55	1.88	0.94

* in gm

Table 3-16 A priori reduction rates for gasoline vehiles (%)

Reduction rates	Cold execss emission			hot emission factor		
	CO	HC	NOx	CO	HC	NOx
from Euro 1 to Euro 2	30	30	50	10	30	50
from Euro 2 to Euro 3	20	40	40		30	40
from Euro 3 to Euro 4	40	40	40	30	30	30
cumulative reduction rates (%) from EURO 1						
to EURO 2	30	30	50	10	30	50
to EURO 3	44	58	70	10	51	70
to EURO 4	66	75	82	37	66	79

Table 3-17 Emissions levels and cold start excess emissions of Euro 3 gasoline vehicles (g/km)

Driving cycle	CO	HC	Nox
UDC-cold	4.77	0.36	0.17
UDC-hot	0.87	0.049	0.06
EUDC	0.6	0.028	0.072
NEDC-cold	2.14	0.15	0.11
NEDC-hot	0.7	0.035	0.066
Cold start excess emission*	15.84	1.24	0.44

* in gm

Table 3-18 Emissions levels and cold start excess emissions of Euro 4 gasoline vehicles (g/km)

Driving cycle	CO	HC	Nox
UDC-cold	2.95	0.22	0.11
UDC-hot	0.61	0.0343	0.042
EUDC	0.42	0.0196	0.0504
NEDC-cold	1.35	0.09	0.07
NEDC-hot	0.49	0.0245	0.0462
Cold start excess emission*	9.5	0.75	0.27

* in gm

Table 3-19 Emissions levels and cold start excess emissions of Euro 1 diesel vehicles (g/km)

Driving cycle	CO	HC	Nox	particles
UDC-cold	0.98	0.17	0.9	0.12
UDC-hot	0.69	0.1	0.88	0.1
EUDC	0.32	0.06	0.55	0.1
NEDC-cold	0.56	0.1	0.68	0.11
NEDC-hot	0.45	0.07	0.67	0.1
Cold start excess emission*	1.18	0.29	0.1	0.077

* in gm

Table 3-20 A priori reduction rates for diesel vehicles (%)

reduction rates	Cold execss emission				hot emission factor			
	CO	HC	Nox	Particles	CO	HC	Nox	particles
from Euro 1 to Euro 2	30	30	40	30	30	30	30	40
from Euro 2 to Euro 3	30	30	30	30	40	30	30	40
from Euro 3 to Euro 4	30	30	30	30	20	30	30	40
cumulative reduction rates (%) from EURO 1								
to EURO 2	30	30	40	30	30	30	30	40
to EURO 3	51	51	58	51	58	51	51	64
to EURO 4	66	66	71	66	66	66	66	78

Table 3-21 Emissions levels and cold start excess emissions of Euro 2 diesel vehicles (gm/km)

Driving cycle	CO	HC	Nox	particles
UDC-cold	0.69	0.12	0.63	0.074
UDC-hot	0.48	0.07	0.62	0.061
EUDC	0.22	0.04	0.39	0.062
NEDC-cold	0.39	0.07	0.48	0.066
NEDC-hot	0.32	0.05	0.47	0.062
Cold start excess emission*	0.82	0.2	0.06	0.054

* in gm

Table 3-22 Corrected emissions levels and cold start excess emissions of Euro 2 diesel vehicles *(Correction due to the modification of the test procedure) in g/km*

Driving cycle	CO	HC	Nox	particles
UDC-cold	0.85	0.14	0.63	0.074
UDC-hot	0.48	0.07	0.62	0.061
EUDC	0.22	0.04	0.39	0.062
NEDC-cold	0.45	0.08	0.48	0.066
NEDC-hot	0.32	0.05	0.47	0.062
Cold start excess emission*	1.48	0.31	0.06	0.054

* in gm

Table 3-23 Emissions levels and cold start excess emissions of Euro 3 diesel vehicles in g/km

Driving cycle	CO	HC	Nox	particles
UDC-cold	0.55	0.1	0.44	0.046
UDC-hot	0.29	0.05	0.43	0.037
EUDC	0.13	0.03	0.27	0.037
NEDC-cold	0.29	0.06	0.33	0.04
NEDC-hot	0.19	0.04	0.33	0.037
Cold start excess emission*	1.04	0.22	0.04	0.038

* in gm

Table 3-24 Emissions levels and cold start excess emissions of Euro 4 diesel vehicles in g/km

Driving cycle	CO	HC	Nox	particles
UDC-cold	0.41	0.07	0.31	0.03
UDC-hot	0.23	0.03	0.3	0.022
EUDC	0.11	0.02	0.19	0.022
NEDC-cold	0.22	0.04	0.23	0.025
NEDC-hot	0.15	0.03	0.23	0.022
Cold start excess emission*	0.72	0.15	0.03	0.027

* in gm

HDV

In analogy to the passenger vehicles a reduction factor is derived in order to adapt the emission factors in a first Stepp to the EURO I technology enforced in 1992 for new engine types and 1993 for all new engines. The following mean values of the test results for well maintained vehicles of the rfrence year 1990 are assumed:

	Nox	VOC	CO	PM
Emissions (g/kWh)	11	0.6	2.5	0.4

Based on the reduction rates, emissions factor for EURO I and II are estimated.

Table 3-25 Reduction rates and emissions factors for EURO I and II HDVs

	Nox	VOC	CO	PM
Reduction rate (%)EURO 1	30	10	10	20
Emissions (g/kWh)	7.7	0.54	2.25	0.32
Reduction rate (%) EURO II	40	20	20	70
Emissions (g/kWh)	6.6	0.48	2	0.12

Related to the engine technologies of the 80s the following reduction rates according to Euro III will be applied to HDV:

Nox 60%, PM 80%.

No reduction is assumed for VOC and CO.

The German Environmental Agency (UBA, 1996) has proposed emission reduction targets from an environmental point of view which may come into force in 2005 or later and may be taken as EURO IV standards for scenario investigation. For CO no reduction targets have been defined because the air pollution concentrations are not of major concern anymore. For Nox UBA proposes a reduction of 75% in relation to EURO II which would result in 1.75 g/kWh in the 13 model test. For PM the UBA proposal is also based on the existing EURO II standard of 0.15 g/kWH in the 13 model test. From scenario investigations the need for a further reduction of 50% was derived leading to a limit of 0.075 g/kWh in the 13 model test. For VOC it was derived a need for a further reduction of 60% but this reduction has to be applied to today's average emissions. In order to assure this emission target by legislation the EURO II standard has to be decreased by 84% (0.18 g/kWh).

The reduction rates which will be defined in the following EURO-IV HDV are based on the UBA emission reduction targets and related to the pre-Euro I state.

Nox 85%, VOC 70%, PM 85%.

New vehicle technologies

Emissions factors for three future vehicle technologies are given which may have significant market penetration over the next 20 years. These include the Electric Vehicles (EV), the Hybrid Electric Vehicles (HEV), and the Fuel Cell Electric Vehicle (FCEV).

Electric Vehicles (EV)

EV is assumed to produce no emissions at the point of use. However, emissions arise due to the electricity consumption which is counted with the electricity generation.

Hybrid Electric Vehicles (HEV)

Table 25 presents the emissions factor for HDVs.

Table 3-26 Emission coefficients for gasoline hybrid passenger cars and LDVs (g/km)

	CO_2	CO	NO_x	HC	PM
Passenger car	112	0.166	0.017	0.01	0
LDV	202	0.299	0.031	0.019	0

Source: MEET, 1998b

Fuel Cell Electric Vehicle (FCEV)

These type of vehicles use hydrogen and oxygen to produce electricity. Hydrogen can be supplied directly to the vehicles or can be drawn from other fuel supplied to the vehicles. Methanol is a good hydrogen carrier and a strong contender for widespread use in fuel cell vehicles (MEET, 1998). Table 26 presents the vehicle emissions factors from methanol FCEV.

Table 3-27 Vehicle emissions factorss for methanol FCEV (g/km)

Vehicle	CO_2	CO	NO_x	HC	PM
Passenger car	113	0	0	0.0046	0
LDV	203	0	0	0.0082	0
Urban bus	979	0	0	0.0397	0

Source: MEET, 1998b

(b) Air pollution related damages

Mortality

To measure the mortality, Years of Life Lost (YOLL) is used to quantify the expected adverse effects on human health resulting from an increase in the concentration of air pollutants (Krewitt et al, 2001). Pollutant-wise YOLL estimates resulting from the emission of one kilo-tonne of pollutant are available for EU-15 region for the years 1990 and 2010 and for the other world region for the year 1990 only (Table 27). Once total pollutions are known, YOLL estimates by pollutant given in Table 5 will be used to determine the YOLL caused by the total pollutions. However, it should be noted that similar to the resource reserves, YOLL is also dynamic (influenced by a number of factors such as population density etc.) and value would change over time as can be seen for EU –15 between the years 1990 and 2010. Therefore, using the value of 1990 for the future years may cause some errors in estimation of the impact.

Table 3-28 Years of Life Lost (YOLL) resulting from the emissions of one kilo-tonne of pollutant (Base year 1990)

Region	YOLL per kt of SO_2 due to		YOLL per kt of NO_x due to formation of nitrate aerosols	YOLL per kt of PM_{10} due to exposure to PM_{10}
	exposure to SO_2	formation of sulfate aerosols		
EU-15 average	1.7	27	28.5	56.7
EU-15 (2010)	1.5	28.7	45.1	56.7
Asia average	2.5	55.2	56.9	130.8
China	4.6	104.7	145.2	131.7
Japan	2.5	36.1	39.7	84.5
South Korea	3.5	50.3	47.6	101
South America average	0.34	4.9	6.8	16.3
Brazil	1.2	13.3	10.9	16.4
State of Sao Paulo	3.9	38.5	52.5	39.9
Colombia	0.33	3.6	6	5.5

Source: (Krewitt et al, 2001)

Morbidity

To measure morbidity changes, we use restricted activities days (RAD). We calculated RAD for different world regions based on the YOLL data given in Table 27, and the exposure –response slopes for RAD and YOLL by various pollutants taken from IER database and work from Friedrich and Bickel (Friedrich and Bickel, 2001). Table 28 presents the RAD per kilo tonne of pollutants.

Table 3-29 Restricted activities days (RAD) resulting from the emissions of one kilo tonnes of pollutants.

Region	RAD per kt of SO_2	NO_x	PM_{10}
EU-15 average	3489.2	5745.2	7222.9
Asia average	7133.5	7248.4	16662.4
China	13530.5	18496.8	16777.1
Japan	4665.2	5057.3	10764.3
South Korea	6500.3	6063.7	12866.2
South America average	633.2	866.2	2076.4
Brazil	1718.8	1388.5	2089.2
State of Sao Paulo	4975.4	6687.9	5082.8
Colombia	465.2	764.3	700.6

Source: Estimated by the authors

Impacts on crop yield and building materials

To measure the impacts on crop yield and building materials, data on damage costs caused by various pollutants are available for EU 15 countries at country level as well as average EU-15 level for the years 1990 and 2010 (Table 29). Data are not available for any other world region. It should be noted that the impacts on crop yield and building materials are time dependent too depending upon several factors like cropping patterns etc. However, in absence of any other estimates, data for EU-15 and for the year 2010 can be used as an approximation for other regions and for the future.

Table 3-30 Impacts on crop yield and building materials. Damage costs resulting from the emissions of one kilo-tonnes of pollutant from the respective source country (Base years 1990 and 2010)

Impact	Pollutant	Year	EU-15
Impact on crop yield	Euro per t of NMVOC due to O_3 formation	1990	723
		2010	617
	Euro per t of NOx due to O_3 formation	1990	-79
		2010	321
	Euro per t of SO_2 due to exposure to SO_2	1990	20
		2010	-31
Impact on building materials	Euro per t of SO_2	1990	81
		2010	79
	Euro per t of NOx	1990	43
		2010	65

Source: (Krewitt et al, 2001)

References

Friedrich. R and Bickel. P, (2001), Health effects: exposure-response functions, in environmental external costs of transport edited by the authors, Springer, Berlin.

IPCC 1994, Radiative Forcing of Climate Change and An Evaluation of the IPCC IS92 Emissions Scenarios, JT Houghton, LG Meira Filho, J Bruce, Hoesung Lee, BA Callander, E Haites, N Harris and K Maskell (Eds), Cambridge University Press, UK. Pp 339.

IPCC 2000, Emissions Scenarios. 2000 Special Report of the Intergovernmental Panel on Climate Change, Nebojsa Nakicenovic and Rob Swart (Eds.), Cambridge University Press, UK. Pp 570.

IPCC 2001, Climate Change 2001: Working Group I: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), J. T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P. J. van der Linden and D. Xiaosu (Eds.),Cambridge University Press, UK. Pp 944.

Klaassen. G and Miketa. A., 2003, Methodologies for Integrating Impact Assessment in the Field of Sustainable Development, (MINIMA-SUD), IIASA Reference No: 02-136 ECS, International Institute for Applied Systems Analysis, Austria.

Krewitt, W., Trukenmüller A., Bachmann T.M., Heck T., (2001), Country specific damage factors for air pollutants: A Step towards site dependent life cycle impact assessment, International Journal on LCA, 6(4), 199-210.

MEET, 1998a, Methodologies for estimating air pollutant emissions from transport, Aggregated emission factor for road and rail transport, Deliverable no. 23, by J.A Cox and A.J Hickman, TRL, UK.

MEET, 1998b, Methodologies for estimating air pollutant emissions from transport, Emissions factor for future road vehicles, Delivearble 26, Laboratory of Applied Thermodynamics, Aristotle University, Thessaloniki.

Nordhaus W.D. and Boyer J., (1999), Roll the DICE again: Economic models of global warming, Yale University.

Rogner, H., H., 1997, An Assessment of World Hydrocarbon Resources. Annual Review of Energy and the Environment, 22:217-262, 1997.

SAUNER 2000, Sustainability and the use of non-renewable resources, prepared by University of Bath, UK, University of Stuttgart, Germany, Montanuniversiät Leoben, Austria, funded by The European Commission, DGXII, Environment and Climate Program, Contract ENV4-CT97-0692.

http://www.dieselnet.com/standards/eu/hd.html

Annex 1

The Emissions Scenarios of the Special Report on Emissions Scenarios (SRES)

A1. The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies).

A2. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

B1. The B1 storyline and scenario family describes a convergent world with the same global population, that peaks in midcentury and declines thereafter, as in the A1 storyline, but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, at a rate lower than A2, intermediate levels of economic evelopment, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

An illustrative scenario was chosen for each of the six scenario groups A1B, A1FI, A1T, A2, B1 and B2. All should be considered equally sound.

The SRES scenarios do not include additional climate initiatives, which means that no scenarios are included that explicitly assume implementation of the United Nations Framework Convention on Climate Change or the emissions targets of the Kyoto Protocol.

Annex 2

Table A2.1: Proved recoverable reserves of coal in million tonnes, at end 1999

	WEC[1]	EIA[2]*	BP[3]
Africa	55 367	61032	57077***
North America	257 966	282 444	257783
South America	21 752	23977	21752
Asia	179040	322394**	984453**
Europe	312 686	391526	355370
Middle East	1 710	1885	
Oceania	42585		
Total World	984 453	1083259	984453

*Data of USA is for 2000, for remaining countries, they are for 1999.

Includes Oceania also, * includes Middle East.

[1] WEC, 2001, [2] EIA website (http://www.eia.doe.gov/pub/international/ieapdf/t08_02.pdf)

[3] BP Statistical Review of World Energy 2003, figures are for 2002.

Table A2.2: Proved recoverable oil reserves in 1999 in million barrels

	WEC[1]	OPEC[2] statistics	Oil & Gas Journal[3]	World oil[4]	BP[5]
Africa	76 967	83504	76700	94900	77400
North America	65 750	30147	54200	50900	49900
South America	93 369	123104	96000	69100	98600
Asia	60 236	44387*	43800*	56500*	38700*
Europe	70 303	86103	75700	84800	97500
Middle East	680 253	678 737	686000	662000	685600
Oceania	4 287				
Total World	1 051 165	1 045 982	1032000	1018000	1047700

[1]WEC, 2001,

Table A2.3: Proved recoverable reserves of natural gas in 1999 (in billion cubic meters)

	WEC[1]	OPEC[2] statistics	Oil & Gas Journal[3]	World oil[4]	BP[5]
Africa	11400	11501	11180	13511	11840
North America	7943	6488	7723	7989	7150
South America	6299	7763	7165	7080	7080
Asia	17106	14757*	12271*	11891*	12610*
Europe	53552	63754	60279	60401	61040
Middle East	53263	52053	55918	67056	56060
Oceania	1939				
Total World	151502	156316	154535	167927	155780

[1]WEC, 2001, [2] OPEC Annual Statistical Bulletin, 2001

[3] Oil and Gas Journal, Vol 99, No. 52, December 24, 2001; [4] World oil, Vol 223, No.8, August 2002, Julf publishing co.

* Includes Oceania also

[5]BP Statistical Review of World Energy 2003, figures are for 2002.

Table A2.4 : Emissions factors for power generation technologies

KW-Klasse	Energy source	Plant type	Year	Elec. capacity at maximum elec.output	Elec. capacity at maximum heat extration	Thermal capacity at max heat extraction	Elec. Effciency at maximum elec. Output	Elec. Effciency at maximum heat. Output	Thermal efficiency with max heat productiond	Specific Emissions					
										CO2	CO	NOx	SO2	CH4	N2O
				[MW]			[%]			g/kWh	mg/kWh	mg/kWh	mg/kWh	mg/kWh	mg/kWh
Condensing mode	Steam coal	Condensing mode	2000	350			46			728	137	549	549	13	31
			2010	350			47			712	134	537	537	13	31
			2020	350			50			670	126	505	505	12	29
			2030	350			52			640	121	485	485	12	28
		Condensing mode	2000	600			46			728	137	549	549	13	31
			2010	600			47			712	134	537	537	13	31
			2020	600			50			670	126	505	505	12	29
			2030	600			52			640	121	485	485	12	28
		Condensing mode	2000	800			46			728	137	549	549	13	31
			2010	800			47			712	134	537	537	13	31
			2020	800			50			670	126	505	505	12	29
			2030	800			52			640	121	485	485	12	28
		IGCC	2000												
			2010	450			51			656	58.156	160	196	12	27
			2020	450			54			620	54.873	152	185	11	26
			2030	450			54.5			609	53.935	149	182	11	25

		IGCC-with CO2 disposal	2000												
			2010	425			45			89	0	182	222	13.3	30.7
			2020	425			48			84	0	170	208	12.5	28.8
			2030	425			48.5			83	0	169	206	12.3	28.5
	Brown coal	Condensing mode	2000	965			44.5			898	161	645	645	12	28
			2010	1050			45			888	160	638	638	12	28
			2020	1050			50			799	144	574	574	11	25
			2030	1050			50			799	144	574	574	11	25
		IGCC	2000												
			2010	450			49			815	70.1	395	599	11.1	26.0
			2020	450			52			768	66.1	372	564	10.5	24.5
			2030	450			52.5			761	65.4	368	559	10.4	24.3
		IGCC-with CO2 disposal	2000												
			2010	425			43			112	0	450	683	12.7	29.6
			2020	425			46			104	0	420	638	11.9	27.7
			2030	425			47			102	0	411	624	11.6	27.1
	Natural gas	Natural gas CC	2000	400			57.5			353	21	272	0	5.0	9.4
			2010	500			60			339	20	261	0	4.8	9.0
			2020	500			62			328	20	252	0	4.6	8.7
			2030	500			63			323	19	248	0	4.6	8.6
		Natural gas CC	2000	800			57.5			353	21	272	0	5.0	9.4
			2010	1000			60			339	20	261	0	4.8	9.0
			2020	1000			62			328	20	252	0	4.6	8.7
			2030	1000			63			323	19	248	0	4.6	8.6

		CC and CO2-disposal	2000												
			2010	450			54			45.1	22.3	290	0	5.3	10.0
			2020	450			56			43.5	21.5	280	0	5.1	9.7
			2030	450			57			42.7	21.2	270	0	5.1	9.5
	Nuclear	European Pressurised reactor	2000	1756			36			0	0	0	0	0	0
			2010	1756			36			0	0	0	0	0	0
			2020	1756			36			0	0	0	0	0	0
			2030	1756			36			0	0	0	0	0	0
Condensing with heat extraction	Natural gas	Condensing-CHP	2000	50	39	54	48	37	50	423	25	326	0	6.0	11.3
			2010	50	39	53	48	37	50	423	25	326	0	6.0	11.3
			2020	50	39	50	49	38	49	415	25	319	0	5.9	11.0
			2030	50	39	48	50	39	48	406	24	313	0	5.8	10.8
		Condensing-CHP	2000	100	82	92	51	42	46	398	24	307	0	5.6	10.6
			2010	100	82	90	52	42	46	391	23	301	0	5.5	10.4
			2020	100	80	83	54	43	45	376	22	290	0	5.3	10.0
			2030	100	80	80	55	44	44	369	22	284	0	5.2	9.8
		Condensing-CHP	2000	200	167	167	54	45	44	376	22	290	0	5.3	10.0
			2010	200	167	163	56	45	44	363	22	279	0	5.1	9.7
			2020	200	159	148	58	46	43	350	21	270	0	5.0	9.3
			2030	200	159	142	59	47	42	344	21	265	0	4.9	9.2
	Steam coal	Condensing-CHP	2000	500	429	583	42.5	35	53	788	148	594	594	14.1	33.6
			2010	500	429	650	44	35	53	761	143	574	574	13.6	32.4
			2020	500	400	578	45	36	52	744	140	561	561	13.3	31.7
			2030	500	402	554	46	37	51	728	137	549	549	13.0	31.0
		Condensing-CHP	2000	300	257	350	42	33	55	797	150	601	601	14.2	34.0
			2010	300	257	428	42.5	33	55	788	148	594	594	14.1	33.6

		IGCC-CHP with CO2 disposal													
				425	344	476	42	34	47	91.3364	0	195	237.857	14.3	34.0
				425	331	434	45	35	46	97.9371	0	182	222	13.3	31.7
				425	336	420	45.5	36	45	93.5093	0	180	219.56	13.2	31.4
	Natural gas	CC and CHP	2000		100	100		45	45	452	27	347	0	6.4	12.0
			2010		100	95.7		46	44	442	26	340	0	6.3	11.7
			2020		100	91.5		47	43	432	26	333	0	6.1	11.5
			2030		100	87.5		48	42	423	25	326	0	6.0	11.3
Back pressure	Steam coal	CC and CHP	2000		200	200		45	45	452	27	347	0	6.4	12.0
			2010		200	193.4		45.5	44	447	27	344	0	6.3	11.9
			2020		200	191.3		46	44	442	26	340	0	6.3	11.7
			2030		200	187.1		46.5	43.5	437	26	336	0	6.2	11.6
		Combined heat and power	2000		200	285.7		35	50	957	180	721	721	17.1	40.7
			2010		200	283.3		36	51	930	175	701	701	16.6	39.6
			2020		200	275.7		37	51	905	171	682	682	16.2	38.5
			2030		200	263.2		38	51	881	166	664	664	15.7	37.5

II. Extensions of Perfect Foresight Models

Hal Turton and Leonardo Barreto (ERIS)	**IIASA**
Leonardo Barreto and Socrates Kypreos (GMM)	**PSI**
Markus Blesl, Ulrich Fahl and Anjana Das (TIMES-G3)	**IER**
K. Smekens (MARKAL-WEU)	**ECN**

1. ERIS

1.1. Introduction

Energy-technology policies, including R&D and demonstration, procurement and deployment programs, are important driving forces in the development of energy systems. Understanding the mechanisms by which technology policies generally, and R&D specifically contribute to long-term energy technology choice, and improvements in the overall energy system, are important for designing strategic policy responses aimed at achieving the goals of sustainable development (Nakićenović 1997). Ideally, an improved and quantitative understanding of the potential impact of technology policies on sustainability could provide policy and decision makers with the insights necessary to formulate the most effective energy-related R&D and complementary strategies.

The SAPIENTIA project , sponsored by the European Commission (DG Research) examines the effectiveness of energy-technology research and development (R&D) activities and demonstration and deployment (hereon referred to as D&D) programs in stimulating the adoption of new technologies, and the consequent impact on a number of sustainability indicators in the areas of climate change, air pollution, transportation, security of energy supply and economic development, all of which represent important challenges confronting policy makers.

Two of these challenges – mitigating the impacts of climate change and maintaining security of energy supply – are prominent issues on both national and international policy-making agendas. The increasing evidence of human-induced interference with the earth's climate system and mounting concern about potentially serious future adverse impacts make global climate change one of the most significant challenges to the realisation of sustainable development in the long term (IPCC, 2001a). Efforts to address climate change necessarily require a focus on the global energy system, which is the major source of anthropogenic greenhouse gas emissions. Accordingly, climate policy calls for, among others, the investigation of low-emissions alternatives for energy production, conversion and final use, including the role of technology support programs (e.g., IPCC 2001b; Hoffert et al. 2002; Hasselmann et al, 2003).

Security of energy supply is considered a more pressing short-term concern by policy makers. An excessive reliance on fossil fuels, oil and natural gas in particular, is an issue of concern because it potentially creates economic, physical and geopolitical risks (EC 2001). Specifically, the current overall dependence of OECD countries on oil supply from politically volatile regions and the definition of appropriate responses to potential supply disruptions remain challenging issues (e.g., DOC 1999; EC 2001; IEA 2001).

Climate change and security-of-supply are complex issues, and overcoming the challenges to sustainability posed by either will in all likelihood require the application of a broad portfolio of policy instruments and support (see Turton and Barreto 2005). This analysis seeks to assess the potential role of two instruments that exploit technological change, which is not only a key driving force behind the anthropogenic contribution to climate change and resource depletion, but may also be an important instrument for mitigating the impact of, and adapting to climate change and energy supply constraints (IPCC, 2001b; Nakićenović, 2003; Turton and Barreto 2005).

The specific policy instruments examined in this study include: energy-related research and development (R&D) investment and energy-related demonstration and deployment (D&D) programs. Both of these policy instruments are examined using the notion of "shocks", i.e., one-off incremental investments in either research and development, or demonstration and deployment (see Turton and Barreto (2003) for a discussion). For each of these policy instruments, we examine the resulting incremental change in a number of sustainability indicators related to climate change and security of supply when the policy instrument is applied, relative to the costs of application of the instrument (measured in €1999s throughout this report). Hereafter, this ratio is referred to as the "impact" of the policy instrument.

The specific climate change indicators considered here comprise: atmospheric concentrations of CO_2 and CH_4, global temperature change and global sea-level rise. In this analysis, these indicators are generally reported for the year 2100 because the inertia in both energy and climate systems means that policy impacts take a long time to fully emerge. The indicators for security of energy supply are long-term global resources-to-production (denoted here as R:P) ratios for oil and natural gas, both of them reported for the year 2060. We discuss the selection of this year in the sections below, but generally, the first decade of the second half of the 21st century may be a time when resources of oil and gas are under significant pressure, but before which the energy system has relatively few opportunities to shift to other energy sources.

This analysis builds on earlier work for the SAPIENTIA project involving development and extension of the energy-systems model ERIS (Energy Research and Investment Strategies) (Turton and Barreto 2003). This development and extension successfully sought to introduce key mechanisms of technological change in energy systems into ERIS, and compute the sustainability indicators of interest, applying the MAGICC climate model (Wigley and Raper 1997; Wigley 2003). Furthermore, relevant key energy technology candidates for R&D and D&D support were also incorporated. More detail on the model extensions is discussed in Turton and Barreto (2003).

1.2. Additional Extensions to the ERIS model

The analysis for the SAPIENTIA project was performed using the modeling framework developed at IIASA-ECS and described in Turton and Barreto (2003). This framework comprises the energy systems model ERIS and the MAGICC climate model (Wigley and Raper 1997; Wigley 2003).

ERIS (Energy Research and Investment Strategies) is a multi-regional "bottom-up" energy-systems optimization model that endogenises learning curves. The original version of the model was developed as a joint effort between ECS/IIASA and the Paul Scherrer Institute (PSI) in Switzerland during the EC-sponsored TEEM and SAPIENT projects, where it was mainly used to examine issues related to the endogenization of mechanisms of technological change (Messner, 1998; Kypreos et al., 2000; Barreto and Kypreos, 2000, 2004).

At the end of 2003, the ERIS model was substantially expanded and recalibrated at ECS/IIASA by the authors in order to address the objectives of the SAPIENTIA project, in particular those related to climate change and transportation indicators. For this purpose, the model was restructured and a number of features added. The main modifications described in the mid-term report (Turton and Barreto 2003), include:

- development of cluster approach to technological learning;
- disaggregation and additional technological detail in the non-electric sector, particularly transportation;
- addition of an energy carrier production sector, specifically for hydrogen, alcohol and Fischer-Tropsch liquids production;
- incorporation of methane and nitrous oxide emissions and abatement cost curves for these gases;
- inclusion of sulfur dioxide emissions; and

- inclusion of geological and terrestrial carbon storage.

In many cases, these modifications to the ERIS model were made on the basis of output from other work packages in the SAPIENTIA project, or the anticipated output in cases where prerequisite work packages were incomplete at the time the mid-term report was prepared. Accordingly, where necessary, the model has been updated and refined subsequent to the mid-term report as prerequisite work packages were completed. For instance, Sections 2.2.3 and 3 in the mid-term report (Turton and Barreto 2003) discussed preliminary approaches to the modeling of two-factor learning and clustering technological learning. Although the main elements of the approaches described in the mid-term report have been maintained, the actual formulation of learning in the ERIS model has been updated to incorporate the two-factor learning and cluster specification of Kouvaritakis and Panos (2005). The modeling of learning is discussed in Section 2.1 below.

Furthermore, the alternative technology specification has required updating of the assumed fossil fuel resources presented in Section 2.1.2 of the mid-term report. The ERIS model now includes around half the unconventional oil resources estimated by Rogner (1997) and referred to as Category VI resources in Table 1 in the mid-term report. These unconventional oil resource were not included in the interim version of ERIS described in the mid-term report, but this revision reflects a less pessimistic assessment of future availability of oil resources consistent with other features of the overall scenario used in this analysis (see Turton and Barreto 2003). Importantly, we continue to exclude highly speculative “additional occurrences” of oil and gas resources.

1.2.1. Learning and Two Factor Learning Curves

Technology learning can be represented in energy system models such as ERIS by incorporating non-linear one or two-factor learning curves (1FLCs, 2FLCs) that represent the impact on technology characteristics of increasing experience or R&D. However, the complexity of the ERIS energy systems model renders it unsuitable for solution with non-linear programming (NLP) methods. With complex non-convex models, NLP solvers are unlikely to find the global optimum, and may experience extremely long run times. Accordingly, in the past, a mixed-integer programming (MIP) formulation of ERIS was used to approximate non-linear learning curves using a piece-wise step function (see Barreto and Kypreos 2000).

However, for the SAPIENTIA project it is necessary to apply two-factor learning curves (2FLCs) to account for the impact of different future research and development (R&D) budget allocations. A sophisticated learning formulation, that incorporates learning-by-doing, learning-by-searching, technology clusters and other features, has been proposed for the project (Kouvaritakis and Panos 2005). Many of the features of this learning formulation can be incorporated relatively easily into an MIP model formulation, including most of the non-linearities. However, the large number of learning technologies, and the errors likely to be introduced by attempting to eliminate all of the non-linearities raise some further challenges. Because it is not realistic to apply a NLP formulation of the ERIS model, and considering both the number of technology policy ‘shocks’ that need to be applied in the SAPIENTIA project and the uncertainty of obtaining optimal solutions, another alternative was chosen that preserved the detailed learning relationships proposed by Kouvaritakis and Panos (2005).

Accordingly, we apply an iterative linear and MIP formulation. This involves iterating between the linear programming (LP) formulation of the model and an exogenous learning sub-module which incorporates the non-linear 2FLC formulations proposed by Kouvaritakis and Panos (2005) [15]. Cumulative installations from the LP model form the input to the learning sub-module, which calculates new specific costs that are fed back to the LP model. The LP model is rerun with these new specific costs to determine new cumulative capacities, which are then processed by the learning module. The process is repeated until there is sufficient convergence. The specific costs

---

[15] An alternative formulation possibility involves iterating between the MIP version of the model and an exogenous module that accounts for the effect of time on the learning curve. However, this would be extremely time-consuming, limiting the extent to which different policy ‘shocks’ could be explored.

at convergence are then applied to an MIP model that accounts for the non-linearities associated with transmission and distribution infrastructure development (see Turton and Barreto 2003).

The main drawback of this approach is that it eliminates foresight regarding the impact of learning on future technology costs. That is, within each iteration technology cost and performance is independent of experience, although experience does affect technology characteristics in subsequent iterations. However, this loss of foresight regarding the effect of technology experience and R&D may in fact better reflect the uncertainty faced by decision makers when selecting the most suitable technologies (for deployment or R&D). Moreover, from a technical standpoint, experiments with this formulation produce results almost identical to the equivalent MIP model, but in approximately 20-35 percent of the time. Accordingly, it is assumed that any errors introduced by implementing learning in this way are smaller than those associated with the alternative of linearising and estimating complex non-linear learning equations. This approach is not only well suited for incorporating the more sophisticated learning formulation that has been proposed for SAPIENTIA, but facilitates more extensive examination of policy shocks.

2. GMM

2.1. Introduction

This section presents the extensions to the “bottom-up” energy-systems GMM model undertaken at the Energy Economics Group (EEG) of the Paul Scherrer Institute (PSI) in the context of SAPIENTIA. The changes allow substantial improvements in the representation of the mechanisms of technological change in the global energy system in the model and in the examination of the role of the energy system in the context of GHG mitigation strategies. In addition, the extensions presented here enhance the capabilities of the GMM modeling framework for the assessment of the impact of policy instruments on energy and climate-related indicators of sustainable development.

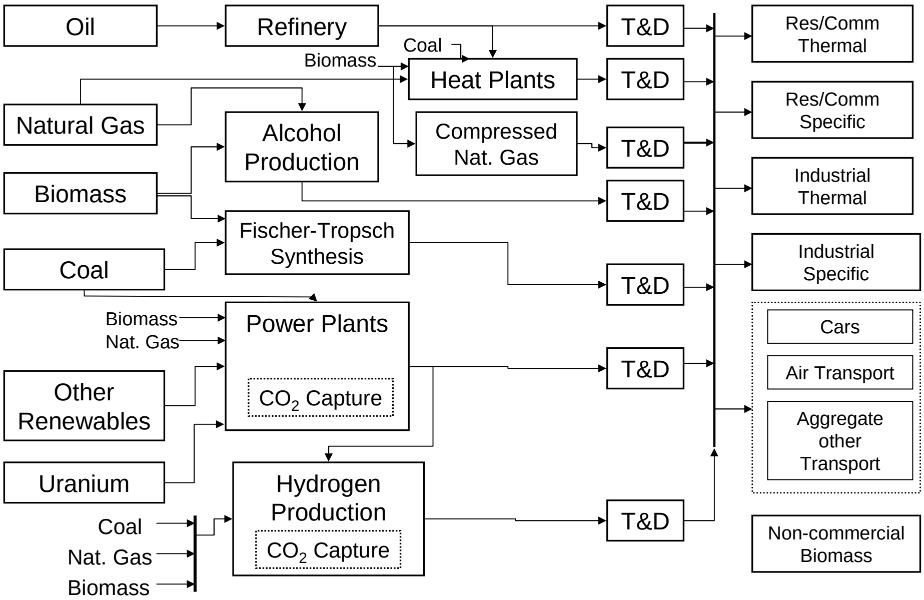
These extensions build upon previous work reported by PSI-EEG to SAPIENTIA, where possible avenues for conducting the assessment were described (Kypreos, 2003). Among the different alternatives described in such work, the GMM model has been chosen because it allows a more comprehensive and detailed representation of technologies in the areas of electricity generation, production of synthetic fuels, transportation and CO_2 capture under examination in SAPIENTIA.

In order to adequately quantify the impact of energy-related R&D and D&D programs on sustainability indicators of interest in the areas of climate change, security of energy supply and transportation, among others, several features have been added to the GMM model. A clusters approach to the representation of technology learning, which allows different technologies to share a common “key learning component”, has been implemented. Also, the representation of the passenger transportation sector has been substantially improved. Moreover, marginal abatement curves for two non-CO_2 greenhouse gases (CH_4 and N_2O) have been added. Other changes are related to the inclusion of additional technologies for production of synthetic fuels (hydrogen and Fischer-Tropsch liquids) and CO_2 capture in fossil-based and biomass-based electricity generation and hydrogen production technologies. In addition, the GMM model has been linked to the simplified climate MAGICC model, in order to estimate several global climate indicators. A detailed description of the extensions made to the GMM model for the SAPIENTIA project can be found in Barreto and Kypreos (2004b).

2.2. Model structure and scenario characteristics

The Global, Multi-regional MARKAL model (GMM) is a “bottom-up” energy-systems model that provides a relatively detailed representation of energy supply technologies and a stylized representation of end-use technologies (Barreto, 2001; Barreto and Kypreos, 2004a; Rafaj et al., 2005). The GMM model, developed and applied at PSI-EEG, is part of the MARKAL family of models (Fishbone and Abilock, 1981; Loulou et al., 2004), a group of perfect-foresight, optimization energy-system models that represent current and potential future technology alternatives through the so-called Reference Energy System (RES). This kind of models is typically used to obtain the least-cost energy system configuration for a given time horizon under a set of assumptions about end-use demands, technologies and resource potentials. Figure 2-1 presents a simplified version of the reference energy system (RES) used in all regions in the GMM model.

Figure 2-1: Reference energy system (RES) used in the energy-systems GMM model



The GMM model comprises five regions. Two regions portray the industrialized world, North America (NAM) and the rest of the OECD countries in the year 1990 (OOECD). One region comprises the economies-in-transition in Eastern Europe and the Former Soviet Union (EEFSU). Two additional regions represent the developing world. The first of them brings together developing countries in Asia (ASIA) and the second region groups Latin America, Africa and the Middle East (LAFM). The model has been calibrated to year-2000 energy statistics (IEA, 2002a,b) and the time horizon is 2000 to 2050 with ten-year time periods. Unless specified otherwise, a discount rate of 5% per annum is used in all calculations.

Assumptions about energy resources and demands for energy services have been taken from the B2 scenario quantified with the MESSAGE model (Messner and Strubbeger, 1995;Riahi and Roehrl, 2000) for the IPCC Special Report on Emission Scenarios (SRES, 2000). The B2 scenario constitutes a “middle-of-the road” development where economic growth, population and other driving forces evolve gradually and in a consistent way with historical trends. Since, among other factors, technology dynamics, time horizon, regional disaggregation, etc, in the GMM model differs from that in the MESSAGE model, we do not claim our PSI-EEG baseline scenario to be a consistent characterization of the B2 storyline of SRES (2000). Still, it could be regarded as one plausible picture of future developments.

In the B2 scenario, economic growth is gradual and differences in the economic growth across regions are reduced slowly along the time horizon. Gross world product increases at an average rate of 2.8% per annum between 1990 and 2050. It grows from 20.9 trillion dollars of the year 1990 (US$1990) in 1990 to approximately 110 trillion in 2050 (at market exchange rates). The population trajectory underlying this scenario corresponds to the updated United Nations median projection (UN, 2004), where world population increases to 9.1 billion people in 2050 (7.8 billion inhabitants in developing regions and 1.3 billion in industrialized regions) in a continuation of historical trends.

Assumptions on the fossil-fuel resource base rely on the estimates of Rogner (1997, 2000) and are consistent with the assumptions of the SRES-B2 scenario. Different cost/volume categories of fossil resources are considered. Conventional and unconventional occurrences for oil and natural gas are included. Conventional occurrences correspond to categories I-IV in Table 2-1 subdivided as follows. Categories I-III represent conventional resources while category IV represents the amount that could be extracted if (existing) enhanced recovery methods are applied to those conventional resources. Unconventional occurrences are represented here only by categories V and VI, although the latter is considered only for natural gas. The categories labeled "additional occurrences" in Rogner (1997, 2000) are not included, due to the uncertainty associated to their amount and extraction costs. Table 2-1 summarizes the regional cumulative fossil resource availability considered here.

Table 2-1: Cumulative fossil resources availability in EJ (adapted from Rogner, 1997, 2000)

	NAM	OOECD	EEFSU	ASIA	LAFM	World
Oil						
• Category I	449	287	861	403	4802	6802
• Category II	478	121	785	320	1410	3114
• Category III	282	175	836	468	1771	3532
• Category IV	746	263	1135	516	3524	6184
• Category V	456	276	200	125	1104	2161
Total	2411	1122	3817	1832	12611	21793
Natural Gas						
• Category I	493	394	1666	336	2501	5390
• Category II	599	227	1914	428	1524	4692
• Category III	652	332	2769	613	2055	6421
• Category IV	350	145	868	182	782	2327
• Category V	2135	1020	1626	1067	1267	7115
• Category VI	3469	2187	2854	1401	2860	12771
Total	7205	3911	10031	3691	8488	33326
Coal						
• Category I	6374	2338	5812	2418	1784	18726
• Category II	0	7287	1051	4032	54	12424
• Category III	4497	1703	2199	13211	1671	23281
• Category IV	5220	3936	23425	7736	1102	41419
• Category V	20881	15747	93697	30944	4408	165677
Total	36972	31011	126184	58341	9019	261527

This information is used to compute relevant indicators of security of energy supply, namely the global resource-to-production (Ru/P) ratios for petroleum and natural gas. In order to compute these indicators, conventional and unconventional resources have been considered.

2.3. Technological learning in the GMM model

The endogenization of technological learning represents an advance in the representation of technological change in energy optimization models, capturing the early investments (i.e. early accumulation of experience and/or R&D knowledge stock) required for a technology to progress and achieve long-term cost competitiveness (Messner, 1997; Nakićenović, 1997). More importantly, it constitutes a key building block of the "causal chain" from R&D and D&D to sustainability indicators, since it makes an important aspect of technological change (i.e. cost development) dependent upon R&D and D&D policy interventions.

The GMM model endogenizes learning curves, where cumulative installed capacity is used as a proxy for accumulated experience (Barreto, 2001; Barreto and Kypreos, 2004a). In a typical one-factor learning curve, the specific investment cost (SC) of a learning technology *te* at the time period t is formulated as follows:

$$SC_{te,t}(CC) = a * CC_{te.t}{}^{-b} \quad (1)$$

Where:

CC: Cumulative capacity

b: Learning index

a: Specific cost at unit cumulative capacity

Usually, instead of the learning index b, the learning rate (LR), i.e. the rate at which the cost declines each time the cumulative production doubles, is specified. The learning rate can be expressed as:

$$LR = 1 - 2^{-b} \quad (2)$$

Also, and in order to avoid unrealistic and over-optimistic reductions in the investment costs of a particular key component, a "floor" cost, i.e. a lower bound for the specific investment costs is specified.

R&D and demonstration and deployment (D&D) can be thought of as two learning mechanisms that act as complementary channels for knowledge and experience accumulation. Within SAPIENTIA, their impacts on sustainability indicators are examined using so-called R&D and D&D "shocks". That is, we examine the change on indicators computed with the modeling system due to a small one-time increment in the R&D knowledge stock or cumulative capacity of a given key learning component.

The so-called two-factor learning curves (hereon referred to as 2FLC) combine the effects of R&D and D&D on technology learning (Kouvaritakis et al., 2000; Barreto and Kypreos, 2004c). In 2FLC, cumulative capacity is used to represent market experience (learning-by-doing) and a knowledge stock function is used to represent the knowledge accumulated through R&D activities (so-called learning-by-searching), respectively (Watanabe, 1995, 1999). The two-factor learning curve for the specific investment costs of a given technology te in the time period t is typically expressed as:

$$SC_{te,t} = a'*KS_{te,t}{}^{-\gamma} * CC_{te,t}{}^{-\sigma} \quad (3)$$

Where:

$CC_{te,t}$: Cumulative capacity

$KS_{te,t}$: Knowledge stock

σ: Learning-by-doing elasticity

γ: Learning-by-searching elasticity

a′: Specific cost at unit cumulative capacity and unit knowledge stock

However, incorporating the 2FLC formulation in an optimization model such as GMM results in a non-linear (NLP), non-convex program (Barreto and Kypreos, 2004b). For such problems, conventional NLP solvers are able to find only locally optimal solutions and global optimization algorithms are suitable only for very small scale problems (Manne and Barreto, 2004). The current size and complexity of the GMM model precludes an efficient solution to the 2FLC non-linear program[16].

---

[16] For the SAPIENTIA project, Kouvaritakis and Panos (2005) have developed an advanced formulation of the 2FLC, which includes, among others, the effects of technological clusters and saturation effects for the learning-by-doing and learning-by-searching elasticities. This formulation is highly non-linear. A heuristic approach for approximating this complex formulation in a perfect-foresight optimization model is discussed in section 2.9 below. However, this approach was not implemented for the GMM model because the size of the model precludes a computationally efficient solution.

Thus, in order to examine the impact of R&D shocks on a key learning component, we have resorted to an approximation outlined in Turton and Barreto (2004). Instead of the 2FLC formulation, a modified form of the 1FLC MIP formulation of the GMM model is used, where the parameters a and b are modified to take into account the effect of R&D activities. In this modified formulation, the parameter a in the 1FLC formulation given in equation 1 above is set to:

$$a = a'^{*}KS_{te,t}^{\ -\gamma} \quad (4)$$

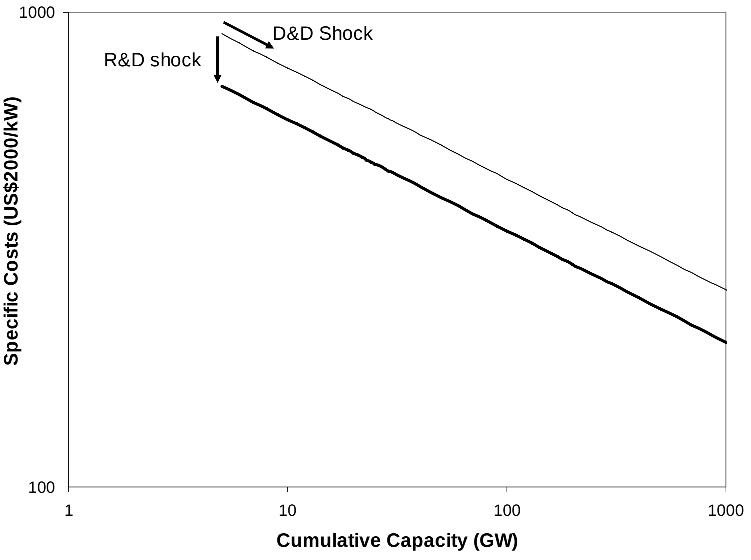
In addition, the parameter b is set to σ. That is, it is derived from the 2FLC specification in equation 3.

In doing so, a R&D shock that increases the knowledge stock (KS) brings a reduction in the parameter a. If the knowledge stock remains constant thereafter, then a remains constant as well. Accordingly, an R&D shock can be incorporated into the single-factor learning formulation by varying a according to Equation 4. This procedure is described in more detail in Turton and Barreto (2004). It should be noticed that this approximation does not allow the model to invest on R&D after the shock.

Demonstration and Deployment (D&D) shocks are simulated as an exogenous investment in a particular technology that leads to the installation of additional capacity. For the purposes of SAPIENTIA, and in order to ensure comparability with the R&D shocks described above, it has been assumed that D&D (capacity) shocks affect a single learning component, rather than an entire technology comprising a number of learning and non-learning components. In reality, however, a D&D program would not consist in the deployment of a single component but of a full technology.

Figure 2-2 presents a simplified scheme that illustrates the respective effects of R&D and D&D shocks in the 1FLC formulation used here. Essentially, an R&D shock will shift the starting point of the learning curve downwards. That is, it will reduce the specific investment cost of the key learning component but will not increase the cumulative capacity. On the other hand, a D&D shock will let the key component move down the learning curve, i.e. by increasing the installed cumulative capacity it will reduce the corresponding specific investment costs.

Figure 2-2: Schematic effect of the Research and Development (R&D) and Demonstration and Deployment (D&D) shocks with the 1FLC formulation used in the GMM model.



2.4. A clusters approach to technological learning

Technologies do not evolve in isolation. Development and adoption of technologies occur as collective evolutionary processes (Silverberg, 1991). Complex interactions where several technologies reinforce and cross-enhance each other drive to the creation of technology clusters (Sahal, 1980), i.e. families of technologies evolving and diffusing together, and to the constitution of associated networks of economic and social actors. Clusters play an important role in technological change. Historically, certain clusters have evolved to become dominant, driving to the conformation of technological regimes (Nakićenović, 1997; Grübler et al., 1999). Technological regimes are difficult to replace because compatible changes are attracted and incorporated by the existing regime while incompatible (radical) changes are discouraged. As a consequence, clusters tend to exhibit a self-reinforcing behavior.

The technologies that constitute a given cluster are related by multiple links that contribute to magnify their economic, social and environmental impacts. These multiple relations contribute to make progress in one of them relevant, directly or indirectly, to other members of the cluster, while contributing to reinforce their own position in the marketplace. Learning spillovers from one technology may trigger improvements in related technologies. Also, performance/cost advances in a particular technology can make a whole energy chain more attractive than others.

It is important to study how technology clusters emerge and evolve, in order to gain insights into the actions that are necessary to promote the introduction of clusters of environmentally sound energy supply and end-use technologies. Therefore, it is necessary to develop an adequate representation of the mechanisms that account for mutual influences between technologies in energy-systems models.

One of those mechanisms is technology learning, i.e. the improvement in cost/performance of technologies as a result of market experience and/or R&D activities. Technological "proximity" may stimulate a collective learning process. Seebregts et al. (2000) have applied the "key technology" concept to the representation of technology learning in "bottom-up" energy system models. This approach allows taking into account one important aspect of technology interdependence, namely the presence of a key common component whose learning spills over the technologies using it (i.e. the key technology). Gritsevskyi and Nakićenović (2000) have also introduced clusters of technologies, defined according to their technological "proximity", considering learning spillovers both within and between different clusters.

Here, following the "key technology" approach implemented by Seebregts et al. (2000) for the European MARKAL model and Turton and Barreto (2004) for the ERIS model, key components have been introduced in the GMM model in the areas of electricity generation, synthetic fuel production (alcohols and hydrogen), CO_2 capture in fossil and biomass-based power plants and hydrogen production as well as passenger cars. Besides providing a mechanism to capture interactions between related technologies as described above, the clusters approach allows extending the number of technologies in which learning takes place while keeping the computational complexity at a reasonable level.

In the clusters approach implemented here, it is assumed that there are full spillovers between technologies belonging to the same cluster. Also, it has been assumed that technology learning takes place at the global scale. Thus, the relationship between the cumulative capacity of a given key component kc and the cumulative capacity of the technologies te that share the component in the time period t is as follows:

$$CCAP_{kc,t} = \sum_{tetokc} \sum_{reg} clust_{tetokc} * CCAP_{te,t} \quad (5)$$

Where:

$CCAP_{kc,t}$: Cumulative capacity of key component kc in time t

$CCAP_{tech,t}$: Cumulative capacity of technology te in time t

tetokc: Mapping set between key component kc and technologies te sharing it

$clust_{tetokc}$: Clustering factor relating the fraction of cumulative capacity of technology te that contributes to cumulative capacity of the key component kc

Learning curves are implemented only for investment costs of the key components. For all the key components, a so-called "floor cost", i.e. a minimum cost level at which the learning process ceases, has been introduced in order to avoid unrealistic cost reductions, according to the guidelines and values agreed upon within SAPIENTIA.

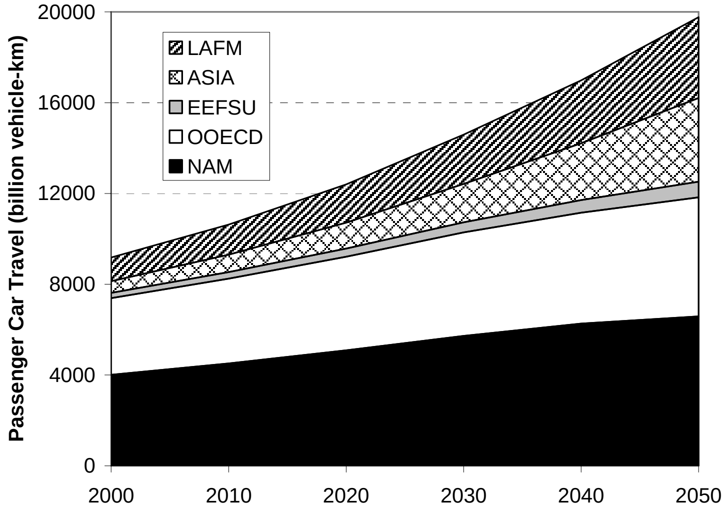
2.5. Disaggregation of the transportation sector

The transportation sector has evolved into a major concern due to its growing energy consumption, its overwhelming reliance on petroleum products and the polluting emissions associated with it. The need to strive towards a sustainable transport system has been widely recognized (IEA, 2003; WBCSD, 2001). Specific attention is required in achieving sustainable mobility in the passenger car sub-sector in the long run, a goal encompassing major technological, economic and social challenges. For SAPIENTIA, the transportation sector has been disaggregated and expanded in order to allow the examination of the impact of specific technologies of interest in the passenger car sector, a major concern for policy makers due to its impacts on the environment and on security of energy supply.

The transportation sector in the GMM model was originally conceived as an aggregate sector where generic technologies were used to mimic final-energy use. The new representation divides the transport sector into three sectors, namely passenger cars, air transport and other transport. For the passenger car mode, a relatively detailed technology representation is introduced. In the other two sectors, a simplified representation has been chosen with generic technologies that mimic the final-energy use.

The demand projection for passenger car mobility used in this scenario has been developed by basically applying the growth rates for passenger mobility in different world regions provided by the WBCSD (2004) to the year-2000 figures of vehicle-km per region estimated by Turton and Barreto (2004,2005). An exception is the ASIA region where a growth rate of 4% per annum has been assumed over the whole time horizon. The assumptions about kilometers driven per car and year for each world region are based on the estimates of Schafer (1995, 1998) and WBCSD (2001). The resulting scenario is presented in Figure 2-3 and shows global passenger car mobility measured in vehicle-km more than doubling between the years 2000 and 2050. The fastest growth occurs in the developing regions (ASIA, LAFM) but a "car mobility divide" between industrialized and developing regions still persists towards the middle of the 21st century.

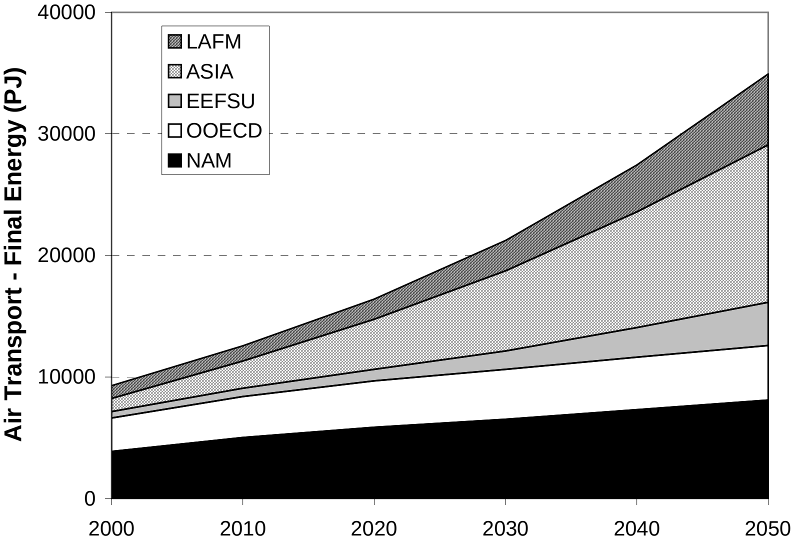
Figure 2-3: Demand projection for passenger car travel per region in the scenario developed here. The description of the regions can be found in section 2.2 above.



As mentioned previously, three main kinds of technologies are incorporated in the database, namely internal combustion engine vehicles (ICEV), hybrid-electric vehicles (HEV) and fuel cell-hybrid vehicles (FCV). The ICEV can be considered as the incumbent, dominant technology which still has some room for improvement. The HEV represents an advanced evolutionary technology, compatible to a good extent with today's dominant technological regime. The FCV, in this turn, is a revolutionary technology, which would require more radical changes to the current technological regime[17]. For each of these technologies several fuels were considered.

The air transport sector has been modeled at the final-energy level. Demands for the year 2000 have been derived from IEA statistics (IEA, 2002a,b). It is assumed that the air transport demand will grow at the same pace as the GDP growth rates of the SRES-B2 scenario (see Figure 2-4). This growth, compounded over 50 years, amounts to an approximately 4-fold increase in global final-energy demand for air transport. Most of the growth takes place in the developing regions, which by the year 2050 account for about 50% of the global final-energy consumption in this sector.

Figure 2-4: Demand projection for air transport per region in the scenario developed here. The description of the regions can be found in section 2.2 above.



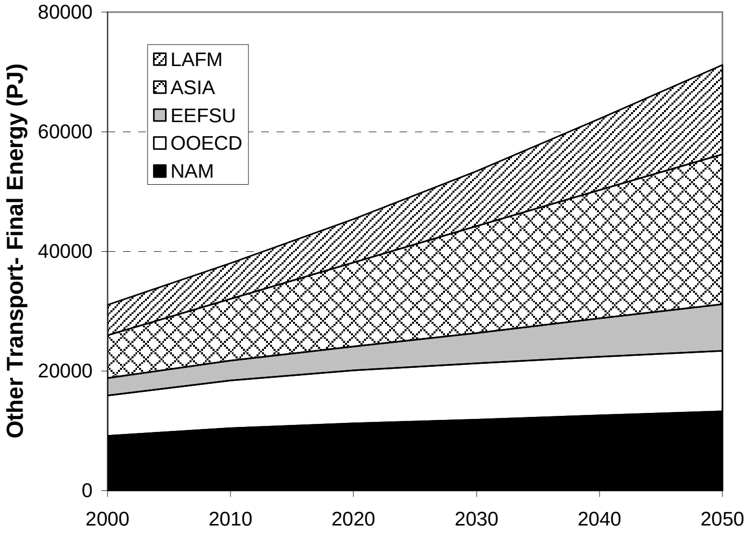
Only two oil-based generic technologies have been considered, under the assumption that other competing technologies, such as hydrogen-powered aircraft would be available only in the second half of the 21st century. The first generic oil-based aircraft technology allows the final energy demand in the air transport sector to grow at the GDP growth rate. The second is a more expensive generic aircraft technology whose fuel efficiency of technology improves over time. The latter allows a decoupling between the growth in final-energy demand in this sector and GDP growth.

The rest of the transportation sector, comprising mainly freight transport, has been considered as an aggregate sector where generic technologies representing the standard use of different fuels (mainly combustion systems) and two advanced fuel-cell systems mimic the final energy consumption. Demands for the year 2000 have been derived from IEA statistics (IEA 2002a,b). Thereafter, regional final-energy demand for other transport is assumed to grow indexed to the GDP projections of the SRES B2 scenario (Figure 2-5). Again, most of the growth in this scenario takes place in the developing regions, which together account for about 60% of the global final-energy demand for other transportation towards the end of the first half of the 21st century.

---

[17] For a discussion of the concept of technological regime see Kemp (1997)

Figure 2-5: Demand projection for other aggregate transport per region in the scenario developed here.



The generic technologies included in the "other transport" sub-sector in the GMM model are as follows:

- Coal-based other transport
- Oil-based other transport
- Natural gas-based other transport
- Electricity-based other transport
- Alcohol-based other transport
- Methanol fuel-cell other transport
- Hydrogen fuel-cell other transport

2.6. Additional technologies

For SAPIENTIA, we have included additional technologies for production of synthetic fuels, electricity generation and CO_2 capture in the GMM model. Specifically, given that Fischer-Tropsch (F-T) liquids (specifically F-T diesel) may have a promising potential as transportation fuels in the medium term, production of Fischer-Tropsch liquids (diesel) from coal and biomass has been included (Steiger, 2000; Hamelinck et al., 2003; Yamashita and Barreto, 2004, 2005). Also, biomass gasification with and without CO_2 capture has been considered in addition to biomass combustion power plants already existing in the model's database. CO_2 capture has been introduce for hydrogen production from coal and biomass gasification and steam reforming of natural gas, following several literature sources (Ogden et al., 2004; Simbeck and Chang, 2002; Parsons et al., 2002; David and Herzog, 2001).

2.7. Incorporation of marginal abatement curves for CH_4 and N_2O

Following the work of Manne and Richels (2004) for the MERGE model and Turton and Barreto (2004) for the ERIS model, we incorporate marginal abatement curves (MACs) for the two main non-CO_2 greenhouse gases, namely methane (CH_4) and nitrous oxide (N_2O), considering both energy-related and non-energy-related sources. This approach uses the regional marginal abatement curves for non-CO_2 GHGs estimated by U.S EPA (2003). By incorporating MACs for these non-CO_2 GHGs, the context for the examination of energy-technology strategies in the GMM model is substantially improved.

Following US EPA (2003), the categories considered in this analysis are as follows: CH_4 emissions from coal, oil and gas production, solid waste management and manure management, N_2O emissions from adipic and nitric acid production. Baseline emissions must be defined for these different sources of emissions. Baseline emissions can be endogenous if they are linked to a model variable or exogenous if they are specified from sources external to the model. In this formulation, energy-related methane emissions from coal, oil and gas production are endogenous to the model. Emissions from other sources are exogenous to the model.

Other sources of CH_4 (enteric fermentation and rice paddies) and N_2O (soils) emissions are also considered exogenously. However, since no MACs are specified for them in the US EPA study (2003), they are treated here as non-abatable emissions. It must be noticed that these sources of emissions currently represent a large fraction of the total emissions of these non-CO_2 gases worldwide (Reilly et al., 2003), but, uncertainties still abound regarding the potential, costs and feasibility of implementation of those measures.

The marginal abatement curves (MACs) are given to the model as stepwise curves relating abatement costs and abatement potentials. These abatement potentials are given either as absolute potentials, e.g. in tons of the respective GHG or carbon-equivalent, or in relative terms (e.g. percentage) of a given baseline. In what follows, it is assumed that the abatement potentials are given as a fraction of the baseline and that emissions from non-CO_2 GHG are expressed in terms of carbon-equivalent (C-eq) emissions using the 100-years global warming potentials (GWP) reported by IPCC (2001), namely 21 for CH_4 and 310 for N_2O. Correspondingly, abatement costs are given in US$/ton C-eq.

The abatement potentials have been derived on the basis of considerations of availability, reduction efficiency and technical and economic applicability of the different abatement options (Delhotal et al., 2003). Abatement potentials per price step, region, and GHG are specified for a reference time period, here chosen as 2010. We did not consider no-regrets options in this specification. That is, all MACs were shifted upwards such that abatement costs are always positive. Abatement potentials for other periods are computed using the so-called technical-progress multipliers (tm). These multipliers represent the fact that abatement technologies may improve over time, thus increasing the abatement potential achievable at a given cost. The multipliers allow extrapolating the MACs beyond 2010, the reference year.

2.8. Linkage to a simplified climate model

The GMM model has been linked to the stylized climate model MAGICC version 4.1 (Wigley and Raper, 1997; Hulme et al., 2000; Wigley, 2003). The GMM model provides energy-related CO_2 emissions, and total emissions of CH_4 and N_2O. Other emissions are exogenously specified following estimates from the IPCC/SRES B2 scenario (SRES, 2000). The link between the energy-system GMM model and climate MAGICC model allows estimating the following global climate indicators: atmospheric concentrations of CO_2, CH_4 and N_2O, annual-average global temperature change and annual-average global sea-level rise, the latter two relative to the year 1990.

2.9. New Formulation of Two-Factor Learning Curves in an Optimization Perfect-Foresight Model

This section describes the new formulation of the Two-Factor learning curve (2FLC) described by Kouvaritakis and Panos (2005a) based on the concept of clusters and applies this formulation to a simplified perfect-foresight optimization model. The purpose of this section is the definition of a heuristic approach that could facilitate the incorporation of these more complex relationships into perfect-foresight models in future exercises. The procedure described here, however, was not used for the generation of the results with the GMM model described in previous sections because the large scale of the GMM model precludes doing so at this stage.

2.9.1. General Specification of the 2FLC equations for clusters

We first present briefly the TFLC formulation introduced by Kouvaritakis and Panos (2005a) for SAPIENTIA using a slightly modified notation and then we adopt the relations for a model with perfect foresight. Let i be a technology, and c be a cluster. Let us then define SCi,t as the capital cost the technology i in time t, CCi,t as the installed capacity of technology i in time t, and KSi,t the cumulative R&D (both Government Energy R&D and Business Energy R&D) spent on technology i at time t.

Then the general formulation of the 2FLC equation as estimated for the SAPIENTIA project is:

$$SC_{i,t} = SC_{i,t-1} \cdot \prod_{c=1}^{l} \left(\frac{cl_{c,t}}{cl_{c,t-1}} \right)^{r_{i,c} \cdot a_{i,t} \cdot} \cdot \left(\frac{CC_{i,t-1}}{CC_{i,t-2}} \right)^{\left(1-\sum_{c=1}^{l} r_{i,c}\right) \cdot a_{i,t} \cdot} \cdot \left(\frac{KS_{i,t-1}}{KS_{i,t-2}} \right)^{b_{i,t}} \qquad (7)$$

with:

$$cl_{c,t} = \sum_{i=1}^{n} w_{i,c} \cdot CC_{i,t-1} \qquad (8)$$

$$a_{i,t} = LBD_i \cdot e^{s_i \cdot \frac{-floor_i}{\left| floor_i - C_{i,t-1} \right| + 1} \cdot caplm_{i,t}} \qquad (9)$$

$$b_{i,t} = LBS_i \cdot e^{s_i \cdot \frac{-floor_i}{\left| floor_i - C_{i,t-1} \right| + 1} \cdot Rdlm_{i,t}} \qquad (10)$$

Equations (9) and (10) calculate the learning coefficients taking into account the “distance” of the capital cost of the technology i in time t-1 from the corresponding floor cost floori (a notional absolute minimum representing a limit to possible improvement). This implement a mechanism for reducing the estimated learning by doing parameter LBDi and the corresponding learning by research parameter LBSi as the capital cost approaches asymptotically the floor cost. Also, these equations define a saturation rate coefficient si, regulating the speed at which saturation is reached. Thus, the final learning parameters, used in the general form of the 2FLC equation (1), are calculated in the equations (3) and (4) and they decline over time as the learning process advances.

In addition, in some cases it has been assumed that the learning parameters are not effective below a threshold either on capacity or on cumulative R&D. This assumption is necessary especially for new technologies in order to avoid learning when only demonstration versions of these technologies exist, mainly in the first years of the analysis, in order to avoid instability in learning arising from an excessive reliance on initial conditions (data and forecasts). Two binary coefficients have been introduced to model this; and , which are defined as follows:

$$caplm_{i,t} = \begin{Bmatrix} 0, & CC_{i,t} \le caplmt_i \\ 1, & CC_{i,t} > caplmt_i \end{Bmatrix}$$

$$rdlm_{i,t} = \begin{Bmatrix} 0, & KS_{i,t} \le rdlmt_i \\ 1, & LS_{i,t} > rdlmt_i \end{Bmatrix} \qquad (11)$$

where and are the capacity and cumulative R&D limits imposed on learning of the technology i. Each technology i has a weight in each cluster c, reflecting the importance of the generic technology defining the cluster c on the cost structure of technology i. Moreover, there is a weight reflecting the importance of the component belonging to cluster c for each technology i adjusted for the learning rate of the cluster. The matrices containing the weights are labelled as W and R respectively (see Kouvaritakis and Panos, 2005a).

With this new formulation, the concept becomes almost a three-factor learning curve. Also, learning is applied to all cost and efficiency data items describing a technology. The original formulation of MARKAL maps the set of technologies to a smaller set of key cluster components where each component retains its learning characteristics. That is:

$$cl_{c,t} = \sum_{i=1}^{n} w_{i,c} \cdot CC_{i,t-1} \qquad (12)$$

Kouvaritakis and Panos (2005a) define the learning performance for the original set of individual technologies but their installed capacity follows the cluster concept. This makes the formulation more complicated and strongly non-linear, especially by the introduction of a third learning term that refers to clusters. Also, the learning parameters are decreasing as long as costs are moving asymptotically towards their floor-cost and are applied to all cost/efficiency data items.

2.9.2. Heuristic approach with stand–alone technologies

It is not possible to apply the previously described non-linear programming (NLP) relations directly in a perfect-foresight model, because it substantially increases the complexity of the model and solvers have problems in identifying an optimal solution for this problem. Therefore, we propose herein a heuristic approach that can approximate the main features of the 2FLC formulation of Kouvaritakis and Panos (2005a). For technologies where the clustering factor can be omitted or where clusters are applied as in a similar approach in the GMM model we can adopt a modified set of equations presented below:

1) Set first the initial values of LBD and LBS

$$a_{it}^{1} = LBD_i \text{ and } b_{it}^{1} = LBS_i \qquad (13)$$

2) Solve the perfect-foresight optimization model as a NLP problem as explained before to estimate the levels of penetration of the technologies, e.g CC_{it}^{n}, KS_{it}^{n} and the specific cost $\mathrm{S}C_{it}^{n}$ for the iteration n

$$\mathrm{S}C_{it}^{n} = SC_{i,0} \cdot \left(\frac{CC_{it}^{n}}{CC_{i0}} \right)^{a_{i,t}} \cdot \left(\frac{KS_{it}^{n}}{KS_{i0}} \right)^{b_{i,t}} \qquad (14)$$

3) Then, based on the previous values and the relations 15 and 16 given below, estimate the new learning rates and for each period as coefficients and solve the perfect-foresight optimization model again. We iterate until the relative error in the technology penetration is within a given limit.

$$a_{it}^{n+1} = LBD_i \cdot e^{s_i \cdot \frac{-floor_i}{\left|floor_i - SC_{it}^{n}\right| + 1} \cdot caplm_{i,t}} \qquad (15)$$

$$b_{it}^{n+1} = LBS_i \cdot e^{s_i \frac{-floor_i}{\left|floor_i - SC_{it}^{n}\right| + 1} \cdot rdlm_{i,t}} \qquad (16)$$

It has been assumed, in some cases, that the learning parameters are not effective below a threshold either on capacity or on cumulative R&D. The two binary coefficients, e.g $caplmt_i$ and $rdlmt_i$ defined before on the capacity and cumulative R&D limits can be introduced as conditions in the perfect-foresight optimization model. Finally, the approach needs the identification of the proper input data for LBD, LBS, floor-costs, initial cumulative levels and the saturation parameters per technology, to be operational. This set of parameters has been estimated for a large number of technologies by Kouvaritakis and Panos (2005a) for the SAPIENTIA project[18].

---

[18] First results show that the method gives similar results as before but is very sensitive to the saturation parameter.

2.9.3. Heuristics with clusters

The next question concerns the possibility of extending the heuristics to the clustering representation described by Kouvaritakis and Panos (2005a). We can define as constants (coefficients) the factors describing the learning characteristics of technologies adjusting them during the iterations hoping that the algorithm will be able to identify a solution when products of approach will converge:

1) Set first the initial values of ac_{it}^{1}, b_{it}^{1} and the cluster factor CLF_{c}^{1} as constants

$$CLF_{c}^{1} = \left(\frac{\sum_{i=1}^{n} w_{i,c} \cdot CC_{i,t-1}}{\sum_{i=1}^{n} w_{i,c} \cdot CC_{i,0}} \right)^{r_{i,c} \cdot a_{i,t}} \qquad (17)$$

The first iteration guess for the coefficients could be defined assuming that the knowledge stock follows the maximum allowable penetration rates by technology:

$$KS_{t} = KS_{0} + RN`\&D_{0} \cdot (1 + g_{rd})^{\Delta t}) \qquad (18)$$

We also need to define the initial values of

$$ac_{it}^{1} = (1 - \sum_{c=1,l} r_{ic}) \cdot LBD_{i} \text{ and } b_{it}^{1} = LBS_{i} \qquad (19)$$

2) Solve the perfect-foresight optimization model as a NLP problem and estimate the levels of technology penetration, e.g. CC_{it}^{n}, KS_{it}^{n} and the specific cost SC_{it}^{n} for the n^{th} iteration:

$$SC_{it}^{n+1} = SC_{i,0} \cdot \prod_{c=1}^{l} CLF_{c}^{n} \cdot \left(\frac{CC_{i,t}}{CC_{i,0}} \right)^{ac_{it}^{n}} \cdot \left(\frac{KS_{i,t}}{KS_{i,0}} \right)^{b_{it}^{n}} \qquad (20)$$

3) Then, based on solution values and the relations 17, 21 and 22 (the latter two specified below), we can estimate the new learning rates and and for each period as coefficients and solve the perfect-foresight model again. We iterate until the relative error in the technology penetration is within a given limit.

$$ac_{it}^{n+1} = (1 - \sum_{c=1,l} r_{ic}) \cdot LBD_{i} \cdot e^{s_{i} \cdot \frac{-floor_{i}}{\left| floor_{i} - SC_{it}^{n} \right| + 1}} \qquad (21)$$

$$b_{it}^{n+1} = LBS_{i} \cdot e^{s_{i} \frac{-floor_{i}}{\left| floor_{i} - SC_{it}^{n} \right| + 1}} \qquad (22)$$

2.9.4. Model application with heuristics for stand–alone technologies

The heuristic approach for approximating the 2FLC formulation of Kouvaritakis and Panos (2005a) explained above has been implemented in a small-scale, stand-alone model of the passenger car sector (Kypreos and Krzyzanowski, 2005; Krzyzanowski, Kypreos *et al.*, 2005) and model experiments were conducted under a perfect foresight formulation. The abbreviations of the passenger car technologies used in the stand-alone model in this exercise are presented in Table 2-2.

Table 2-2: Abbreviations of the passenger car technologies used in the stand-alone model

Technology	Description
TGSL	Conventional gasoline Internal Combustion Engine (ICE) car
TGSA	Advanced gasoline ICE car
TDSL	Conventional diesel ICE car
TDSA	Advanced diesel ICE car
THYB	Oil products hybrid-electric car
THFC	Hydrogen fuel cell car
TMFC	Methanol fuel cell car
TELC	Electric car

Figure 2-6 to Figure 2-10 present selected results of the application of the heuristic approach described above. Figure 2-6 presents the market shares of passenger car technologies when the saturation factor of the learning-by-doing (LBD) and learning-by-searching elasticities (LBS) is set to one (1) for all technologies. Under these circumstances, only the conventional gasoline ICE car penetrates the market.

Figure 2-6: Market penetration of passenger car technologies in the stand-alone transportation model used for this exercise when the saturation factor is equal to 1. As can be seen, only the conventional gasoline car penetrates due to a strong reduction in its LBD and LBS elasticities.

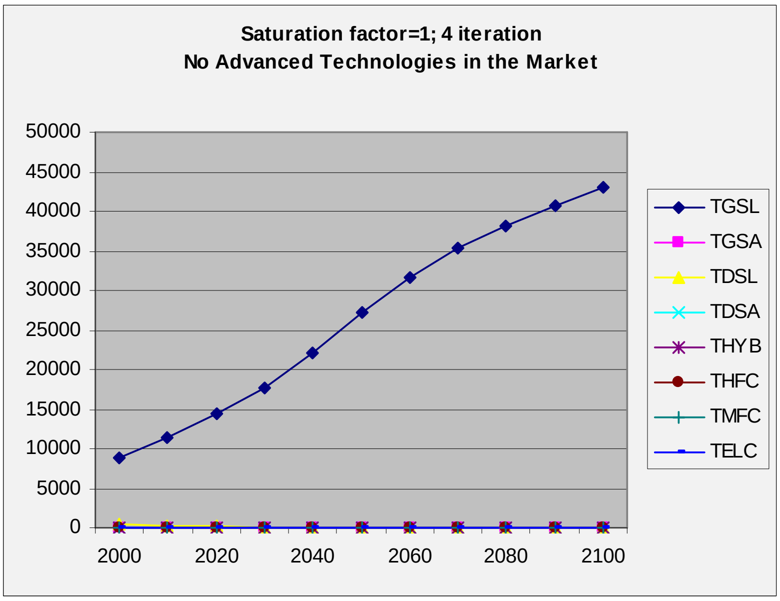


Figure 2-7 and Figure 2-8 compare the market shares of the passenger car technologies when the saturation coefficient (s) for LBD and LBS elasticities is set to 0.01 after two and four iterations of the heuristic approach, respectively. The approach converges after four iterations. After two iterations, the conventional gasoline ICE car penetrates first to be eventually replaced by the oil products-based hybrid-electric car. In addition, hydrogen fuel cell cars are able to gain a small market share. After four iterations, the basic dynamics of the conventional gasoline ICE car being replaced by the oil products-based hybrid-electric car remains but hydrogen fuel cell cars are able to gain a substantial market share towards the end of the time horizon.

Figure 2-7: Market penetration of passenger car technologies in the stand-alone transportation model used for this exercise when the saturation factor (s) is equal to 0.01. Two iterations. The gasoline car penetrates first to be replaced by hybrid cars and a small market share for hydrogen cars.

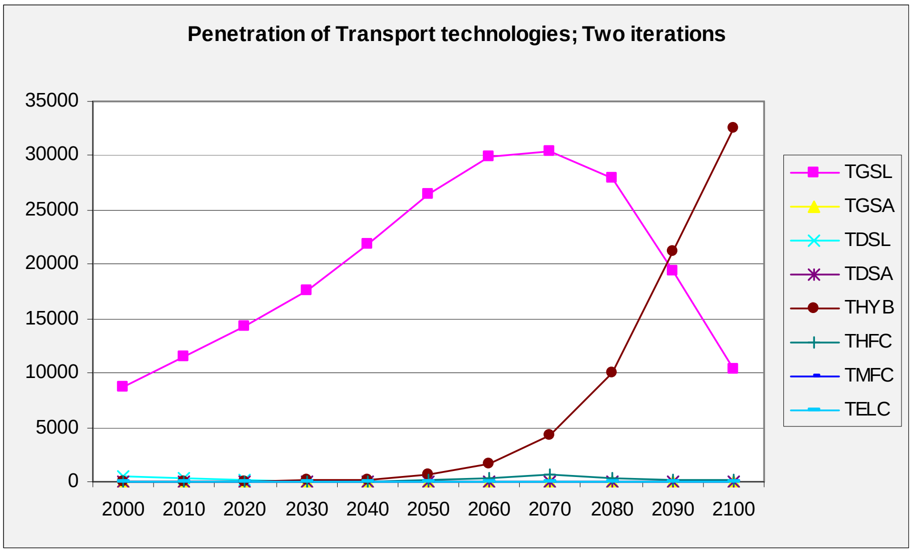
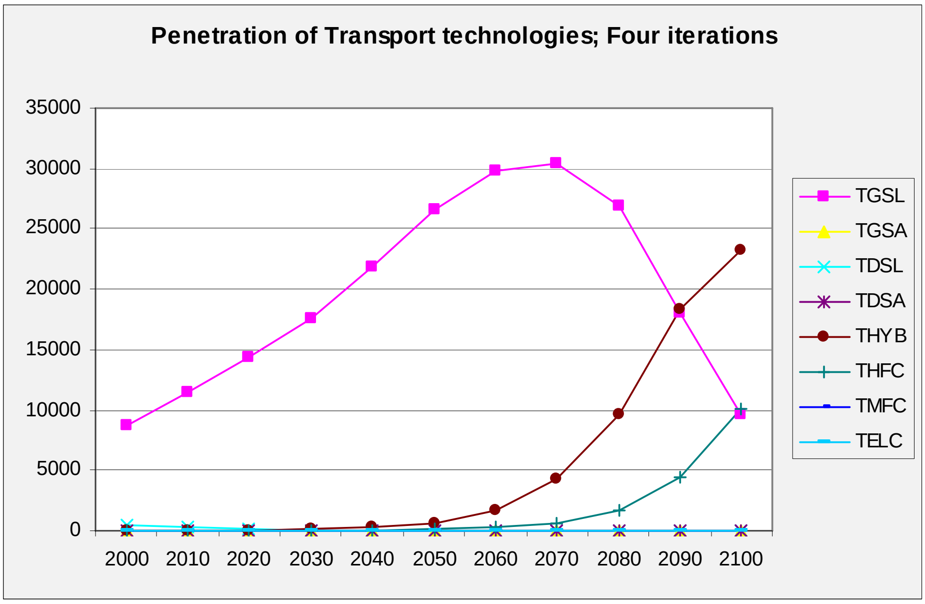


Figure 2-8: Market penetration of passenger car technologies in the stand-alone transportation model used for this exercise when the saturation factor (s) is equal to 0.01. Four iterations. The gasoline car penetrates first replaced by hybrid cars followed by the maximum possible market share for hydrogen cars.



For this case (i.e. saturation parameter set to 0.01), Figure 2-9 and Figure 2-10 compare the evolution of the learning-by-doing (LBD) and learning-by-searching (LBS) elasticities of the hydrogen fuel cell car and the oil-based hybrid-electric car over time. It can be observed that both LBD and LBS elasticities for the hydrogen fuel cell car are high at the beginning of the time horizon but decline strongly towards the end of it.

Figure 2-9: LBD elasticity (learning-by-doing) as function of time. As can be seen, elasticities are reduced to very low values.

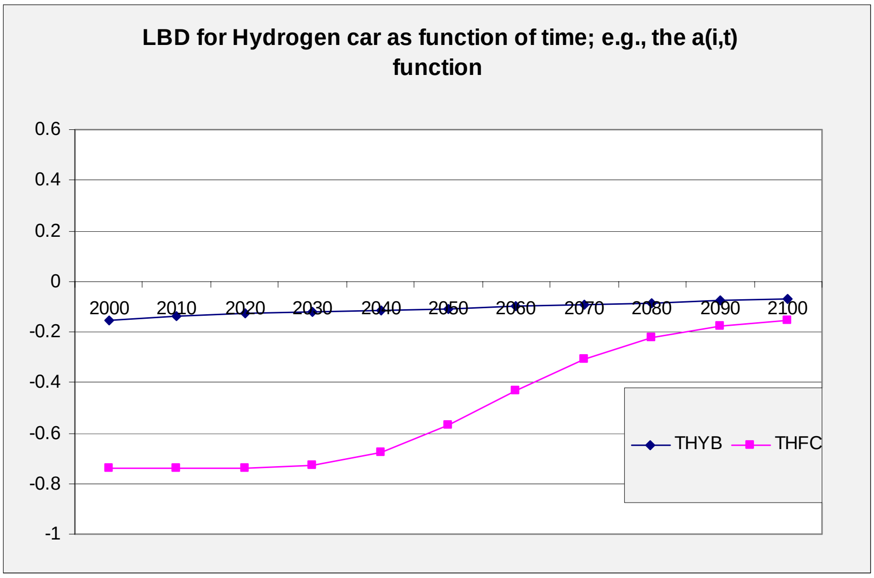
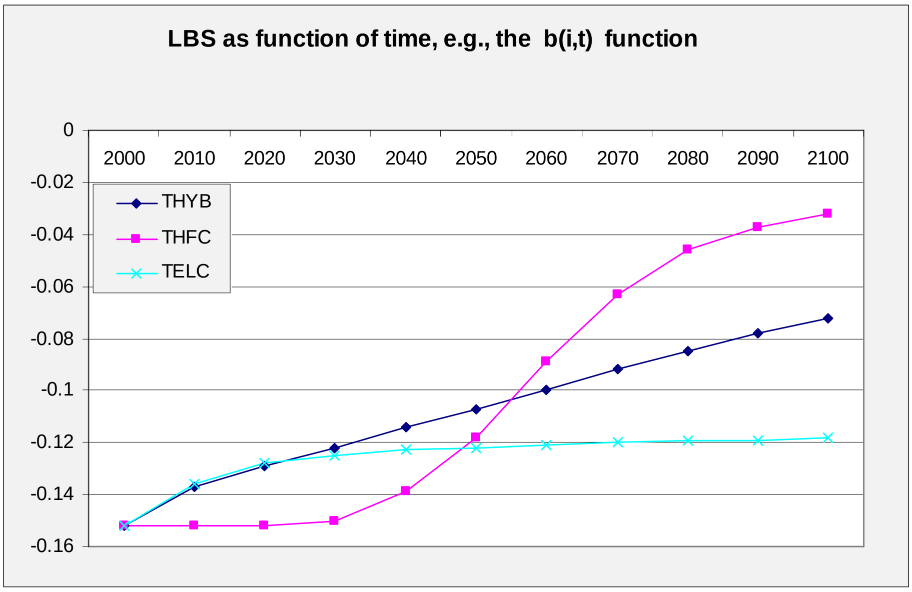


Figure 2-10: LBS elasticity (learning-by-searching) as function of time. As can be seen, elasticities are reduced to very low values



The results are finally dictated to a large extent by the growth rates of the competitive technologies assumed and in this particular case, needed four iterations to be stabilized. They are exactly the same as described in the previous section using fixed coefficients for LBD and LBS. This means that one could apply the methodology in a larger model like the integrated-assessment MERGE model (Manne and Richels, 2004; Kypreos, 2005) once all technologies are described either as stand-alone technologies or as by the clusters approach to technological learning in the energy-system GMM model (Barreto and Kypreos, 2004b), provide the size of the model does not preclude its solution as a NLP problem.

3. TIMES

3.1. Introduction

Modelling of energy systems holds a certain purpose and bears the fundamental concept of energy demand fulfilment economically. Each energy systems model is supported by a large amount of data, a unique framework for the Reference Energy System (RES) and it requires a certain coded framework for data assimilation and handling. The satisfaction of energy demand at the lowest costs and least environmental impact is an important factor for the energy systems models development and the modeler has to draw attention towards the technological development subject to reduction of costs and environmental parameter associated with it. Also, energy systems modeling simulates the behavior of future energy systems and the interplay among technologies, taking in account present situations, social acceptance towards certain technologies, fuel availability, government policies, pollution and other related factors. The basis for satisfying the energy demand in a region of study, needs the cooperation of factors like: exploration at present and in the future, resource and reserve availability, allocation and diversification of resources, international trade etc.

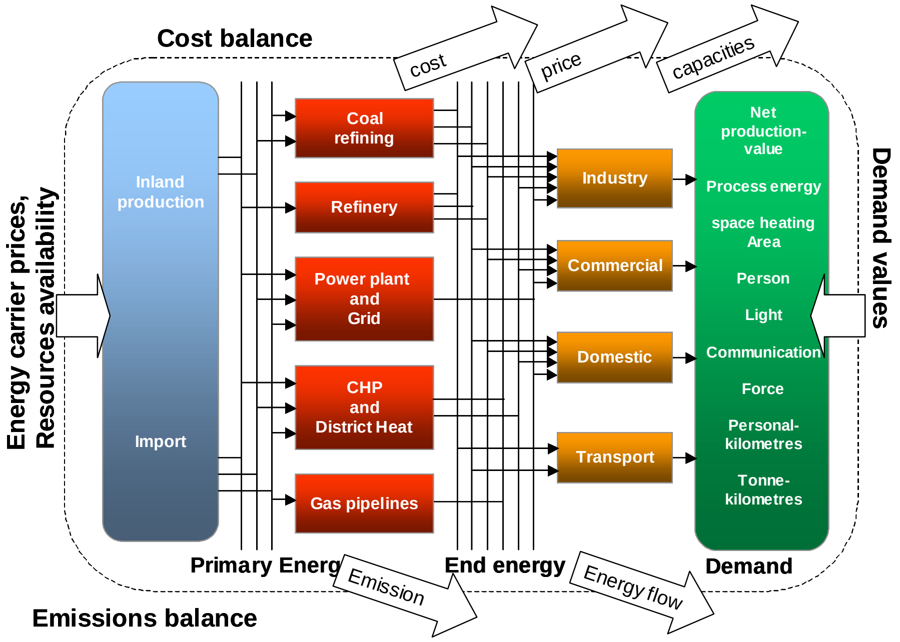
This section focuses on the development of a three regional global energy systems model, it's basic building blocks and peripheral devices. TIMES, the bottom-up linear programmed model generator, is used for the development of the model and ANSWER/VEDA is applied as it's interface. The development of the model on the basis of a reference energy system and the framework of data are provided inside this report. The reserve and resource in each region is modeled by using default cost-potential curve taken from the SAUNER project /SAUNER 2000/ and the transport costs for hard coal, crude oil and natural gas in between regions are calculated. A two factor learning curve has been implemented by mixed integer programming in order to realise the technological dynamics and dissemination inside the energy system by R&D investment. The study specially takes account of government R&D expenditure, which was utilized for new, advanced, efficient and climate compatible technologies to understand it's diffusion inside the future energy system. Government R&D is assumed in this activity as it is comparatively easy to get the public (government) R&D expenditure towards the specific technology development rather than R&D expenditure by private (industry) for the same specific technology.

3.2. An overview of TIMES and the three regional global energy model

TIMES (**T**he **I**ntegrated **M**arkal **E**fom **S**ystem) is a process-analytic, dynamic optimization model of the entire energy system. It was developed within a working group of the Energy Technology System Analysis of Programs (ETSAP) of the International Energy Agency (IEA) /Remme et al. 2001/, /ETSAP 2002/). The TIMES development pursues advantages over existing energy system models like MARKAL /Goldstein, Greening 2001/ and EFOM /Voort et al. 1984/ by eliminating some shortcomings in these models and creating a modeling environment being readily adaptable to new ideas and methodologies. TIMES is a model generator and follows a bottom-up system engineering approach with a detailed technical description of the energy system with interconnectedness of processes (e.g. types of power plants, technologies of transportation) and commodities (energy carriers and shape of energy, material) in form of a so-called Reference Energy System (RES) in which the commodities flow through the processes, while the process themselves represent certain technologies (Figure 3-1). This approach facilitates to depict diagrammatically the whole energy system starting from production to sector-wise useful energy consumption through different conversion processes. Additionally, it is possible to illustrate details of separate sectors like centralised electricity and heat generation, decentralised electricity and heat generation and various sectors like industry, commerce, agriculture, residence, transport, non-energy use etc.

The energy system is interpreted mathematically by different equations of equalities and inequalities subject to optimisation of the objective function, representing the cost (minimisation) or profit (maximisation) by fulfilment of the energy demand. Apart from this there are different goals behind the development of different global, regional, local and sectoral energy models, which solely depend on the developers and their objectives. TIMES is a least cost optimisation model, which reflects the optimisation of the entire energy systems costs in a given time frame. The optimisation criteria includes the reserve and resource availability, the present and future development of energy carrier prices, technological details on existing, new and future investments with the respective parameter associated with it, the energy demand and it's future growth as well as the technological growth. The technologies compete among each other to provide the energy demand with lowest cost by the techno-economic parameter associated with them. As a result of the optimisation the arrangement of the technology inventory is obtained, i.e. the kind and scale of technologies, the necessary input of energy divided into energy sources, costs of the energy system as well as the generated emissions of the greenhouse gases and air pollutants. By running different scenarios it is possible to analyse the behaviour of the model towards different kinds of question, such as the most economically efficient implementations to decrease the amount of greenhouse gas emissions, which comply with technical and ecological restrictions.

Figure 3-1: Schematic illustration of a reference energy system



Based on TIMES, the Institute of Energy Economics and the Rational Use of Energy (IER) of the University of Stuttgart has developed a three regional global energy model, in which the world has been divided into three regions: European 25 nations (EU25), rest of OECD (R_OECD) and rest of Non-OECD (R_NOECD). It is a demand driven, bottom-up and technology abundant model, in which GDP and population are the main drivers for the energy demand development. It is a long time-horizon model (1990-2100) of 19 periods with unequal period lengths. Each year is divided into three seasons and each season is divided further into day and night as the smallest time resolution. At present the study has been intensified for the time frame of 1990-2050.

The entire energy system is represented in Global TIMES-G3 model by extraction, inter-regional exchange, refineries, H_2 production and consumption, synthetic fuel production and consumption, electricity and heat production and consumption sectors like industry, commerce, residence, transport and non-energy use. The energy demand in the industrial sector is divided into three types of useful energy demand. It is categorized as high temperature heat (process heat), medium temperature heat and low temperature heat. Likewise the energy demand in the commerce sector is divided into useful energy demand of heating, cooling and other electricity and in the residential sector into heating, cooling, cooking and other electricity. The transport sector consists of freight and passenger transport by various modes of transportation. The power and heat production sector consists of electricity, heat and co-generation technologies whereas the industrial, commercial and residential sectors contain stationary heat and electricity producing technologies. Commissioning, decommissioning and existing capacities for refinery, electricity producing technologies and for some other sectors, are inserted inside the model. A stepwise extraction capacity of energy carriers and their exploration costs are taken into account /SAUNER 2000/. Environmental pollutants like CO_2, CH_4 and N_2O are included inside the model for GHG evaluation. Potentials and cost of renewables are taken from various sources.

3.2.1. Framework of data

Data are the basic blocks of any energy systems model and largely consistent datasets with proper correlation are required for the improvement of a model. Demographic development and population growth are two important factors which determine the demand inside the TIMES G3 model. Primary energy carriers are modelled with an inter-regional exchange between regions and respective extraction costs for each region. Energy carriers, like hard coal, lignite, crude oil and natural gas, are modelled in four steps having period wise import-export prices, extraction costs and maximum possible amounts which can be extracted.

The final energy demand for the industry, commercial and residential sector is divided into different useful energy consumption by end use technologies. The key indicators for energy intensities of final and useful energy demands are defined and projected until the end of the model horizon. The final energy consumption by the non-energy sector and the indicators for past, present and future have been calculated and provided to the model. In the transport sector the demand (in person and ton-kilometres) has been projected for passenger and freight transport and key indicators are defined for person and ton-kilometre demand. Past investment data for existing technologies in all sectors are calculated and given in the model. Data for electricity transmission efficiency, load curves for heat and electricity, reserve margins, peak load to average load ratios and energy conservation potentials in terms of increase in efficiency have been included. The socio-economic data of the G3 model taken inside the study is provided in the Table 3-1.

Table 3-1: Socio-economic framework data for G3 model

Years	Units	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
European twenty five nations (EU25)														
GDP	B €(00)	7315	7817	8939	10080	11433	12887	14462	16169	18020	19413	20913	23090	24874
GR	%/a		1.34	2.72	2.43	2.55	2.42	2.33	2.26	2.19	1.50	1.50	2.00	1.50
Pop.	Million	441	460	465	459	461	462	462	461	458	454	449	445	440
GR	%/a		0.83	0.22	-0.26	0.11	0.05	-0.01	-0.05	-0.12	-0.18	-0.22	-0.18	-0.23
GDP/Pop.	B €(00)/M	16.58	17.01	19.24	21.98	24.79	27.88	31.30	35.07	39.33	42.76	46.58	51.89	56.53
Rest of OECD nations (R_OECD)														
GDP	B €(00)	13944	16472	18404	20252	21888	24071	26132	28901	31527	32250	32867	32664	32850
GR	%/a		3.39	2.24	1.93	1.57	1.92	1.66	2.04	1.75	0.45	0.38	-0.12	0.11
Pop.	Million	608	641	677	692	709	723	738	754	771	772	773	770	767
GR	%/a		1.07	1.10	0.43	0.50	0.38	0.41	0.43	0.46	0.02	0.02	-0.08	-0.08
GDP/Pop.	B €(00)/M	22.94	25.69	27.19	29.29	30.88	33.31	35.43	38.36	40.89	41.78	42.54	42.44	42.85
Rest of Non-OECD nations (R_NOECD)														
GDP	B €(00)	13104	15974	18818	24364	29908	36358	42807	51584	60361	70185	80008	91974	103944
GR	%/a		4.04	3.33	5.30	4.19	3.98	3.32	3.80	3.19	3.06	2.65	2.83	2.48
Pop.	Million	4087	4493	4900	5245	5590	5945	6300	6636	6971	7238	7505	7717	7929
GR	%/a		1.91	1.75	1.37	1.28	1.24	1.17	1.04	0.99	0.75	0.73	0.56	0.54
GDP/Pop.	B €(00)/M	3.21	3.55	3.84	4.65	5.35	6.12	6.79	7.77	8.66	9.70	10.66	11.92	13.11

(Note: GR stands for growth rate)

3.2.2. Reserves and resources

Resources are defined as “concentration of naturally occurring solid, liquid or gaseous material in or on the earth’s crust in such a form that economic extraction of the commodity from the concentration is currently or potentially feasible" /USA.mining 1980/. From a geological point of view, resources are categorised into identified and undiscovered. Identified resources are those, whose location, grade, quality and quantity are already known or can be estimated in a specific geological condition. With a varying degree of geological uncertainty, identified resources can be divided into demonstrated (measured + indicated) and inferred. Undiscovered resources are quantities anticipated to exist under analogous geological condition with different degrees of probability. Reserves are part of the identified resources that can be economically extracted accompanying existing technological limits.

Table 3-2: Combined reserves and resources potentials of energy carriers by regions predicted by sources

Hard Coal by Various Sources [Gtoe]					
Sources	**World**	**EU25**	**R_OECD**	**R_NOECD**	**State of Information**
SAUNER 2000	3672.10	320.50	700.50	2651.10	1996/1999
DOE/EIA 2001	722.00				2000/2001
WETO 2003	0.00				1996
WEC 2003	549.48	16.44	189.56	343.48	2002
SSB ISY 1999				659.47	1998
BP 2004	381.52	44.83	131.63	205.06	2003
Model Assump.	**3672.10**	**320.50**	**700.50**	**2651.10**	
Lignite by Various Sources [Gtoe]					
SAUNER 2000	773.10	24.10	201.60	547.40	1996/1999
DOE/EIA 2001					2001
WETO 2003					1996
WEC 2003	115.84	12.50	54.01	49.34	2002
SSB ISY 1999				75.78	1998
BP 2004	342.07	62.18	132.75	147.13	2003
Model Assump.	**773.10**	**24.10**	**201.60**	**547.40**	
Gas by Various Sources [Gtoe]					
SAUNER 2000	2333.40	82.10	563.80	1687.50	1996/1997
O&J 2003	148.16				2004
WETO 2003	416.65				1996
Cedigaz 2004	154.29				2004
SSB ISY 1999				20.21	
BP 2004	151.52	2.81	15.44	133.27	2003
Model Assump.	**2333.40**	**82.10**	**563.80**	**1687.50**	
Crude Oil by Various Sources [Gtoe]					
SAUNER 2000	881.71	8.68	341.52	531.61	1993/1996/1997
O&J 2003	399.13	9.81	68.68	320.65	2004
WETO 2003	612.00				1996
O&GJ	173.42				2003
World Oil	143.97				2003
BP 2004	157.26				2003
OPEC 2003	120.82				2003
USGS 2000	360.00				1996
SSB ISY 1999				7.76	1998
BP 2004	156.09	1.16	11.02	143.92	2003
Model Assump.	**881.71**	**8.68**	**341.52**	**531.51**	

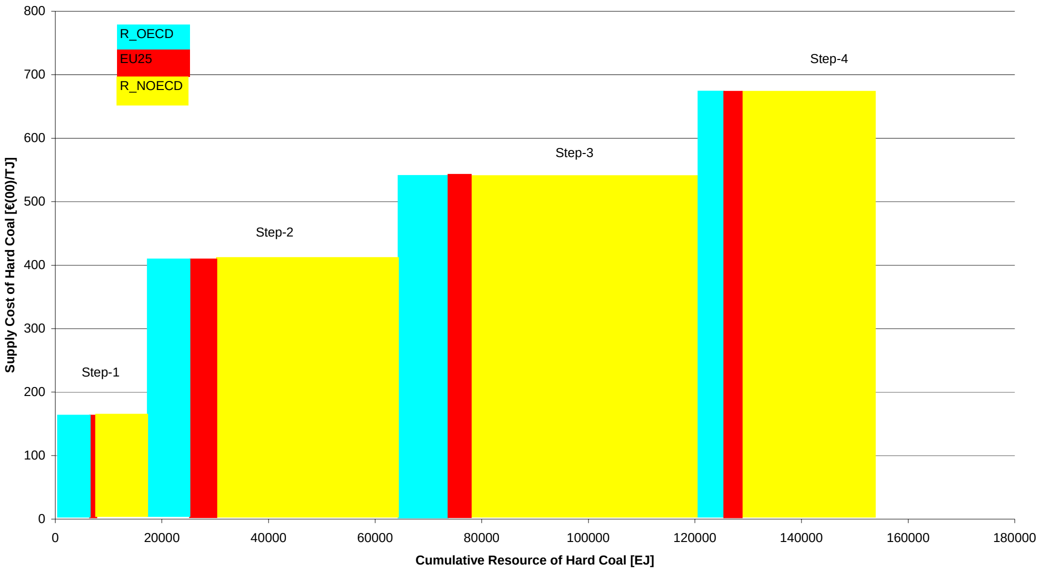
(Note: SAUNER projection on reserve and resource of fuels comes from many sources)

The resources and reserves potentials of different energy carriers by region has been obtained from different sources, which may differ concerning their methods of calculation, assumptions and aggregation of fuel carriers. In this SAPIENTIA project work, the reserves and resources potentials for the three regional world model has been collected and implemented in four modelling steps into TIMES. SAUNER gives the highest projection out of all sources due to the consideration of conventional and unconventional sources. In case of crude oil it includes crude oil and liquid natural gas as conventional source and oil shale, tar sand and extra heavy oil, heavy oil, natural bitumen and extra heavy oil as conventional source. In natural gas reserve and resource calculation gaseous natural gas and liquid natural gas are included as a conventional source and coal bed methane as an unconventional source. Out of the different resource and reserve values existing from the mentioned sources, for TIMES G3 the highest values have been implemented. This can be explained by the expected technology development for extraction and exploration in the future, which may locate more resources. All projection values of energy carriers by sources and model-assumed values are provided in the Table 3-2. The acronym EU25, R_OECD and R_NOECD stands for European Union (25 countries), Rest of OECD and Rest of Non-OECD countries respectively.

3.2.3. Supply-cost curve of energy carriers

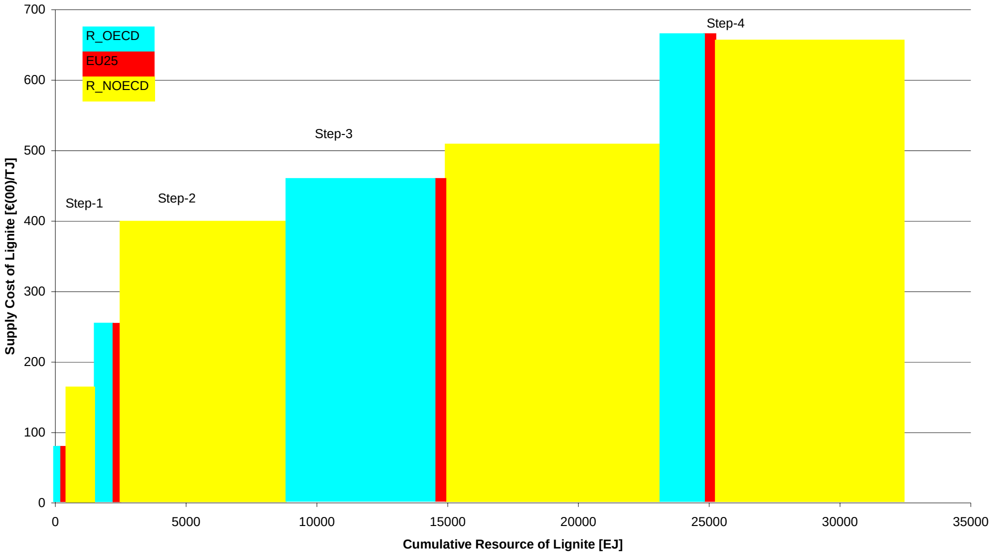
The supply-cost function demonstrates the economic extraction of resources under specified geographical and geological condition with the existing technological limitation. It is an ultimate product for availability assessments, in which discrete reserve/resource quantities are cumulatively arranged in an increasing order of extraction costs. The extraction inevitable depletes the reserves. The exploration and conversion of resources into reserves is accomplished by technological improvement, which is the fundamental component for lowering the extraction cost.

Figure 3-2: Supply-cost curve of hard coal with starting year 1990



The supply-cost curve of hard coal, lignite, natural gas and crude oil are depicted in a four step diagram by regions. The cost-potential curve of energy carriers are based on default cost curves adopted from /Adelman 1993/ and /Rogner 1997/. Furthermore technological improvement has been reflected by reduction of extraction cost by 0.5% per year. The cost of extraction in €(00)/TJ represents the average value for the whole model period, i.e. from 1990-2050. The behaviour of the extraction cost to the amount of extraction can be easily realised from the given figures.

Figure 3-3: Supply-cost curve of lignite with starting year 1990



The production cost of any energy carrier is highly variable depending on geographical, geological and physical characteristics. As for the case of crude oil and natural gas, it depends upon the depth and flow rate of oil, which again depends on physical features like reservoir pressure, permeability, porosity, and water saturation. Major cost development for the extraction site is utilised as investment costs and it depends heavily on the depth of extraction. Sometimes it increases exponentially /DeLuca 1998/ but on other hand, higher flow rates reduce the extraction specific costs per unit of energy. The extraction costs of crude oil and natural gas are also highly variable over time, due to the Hubbert-production function. Out of the figures it can be concluded that the extraction costs for hard coal and lignite do not show the same drastic changes like natural gas and crude oil towards their last phase of extraction.

Figure 3-4: Supply-cost curve of natural gas with starting year 1990

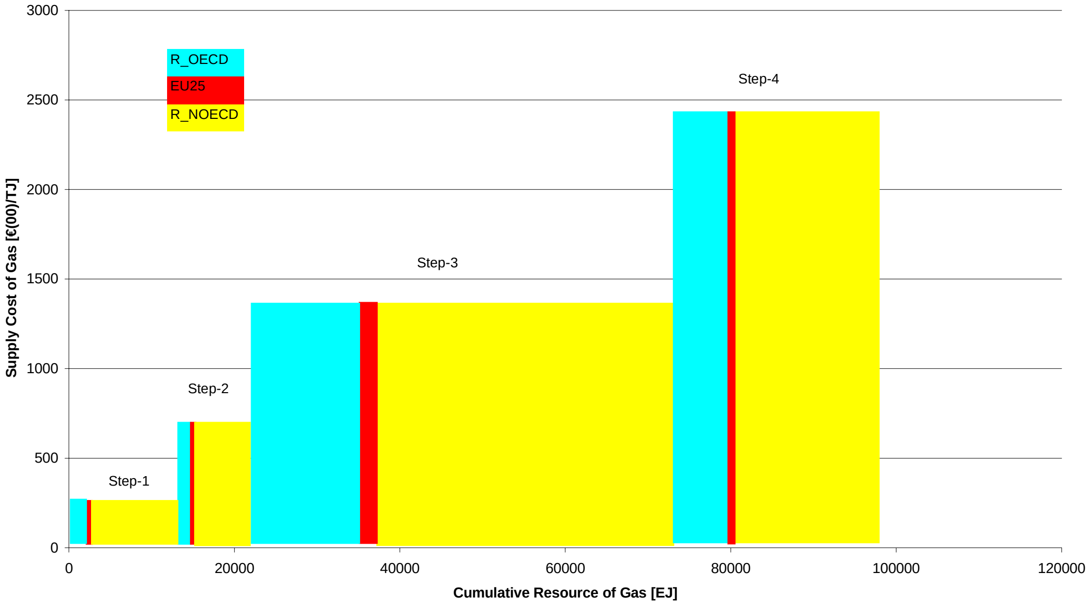
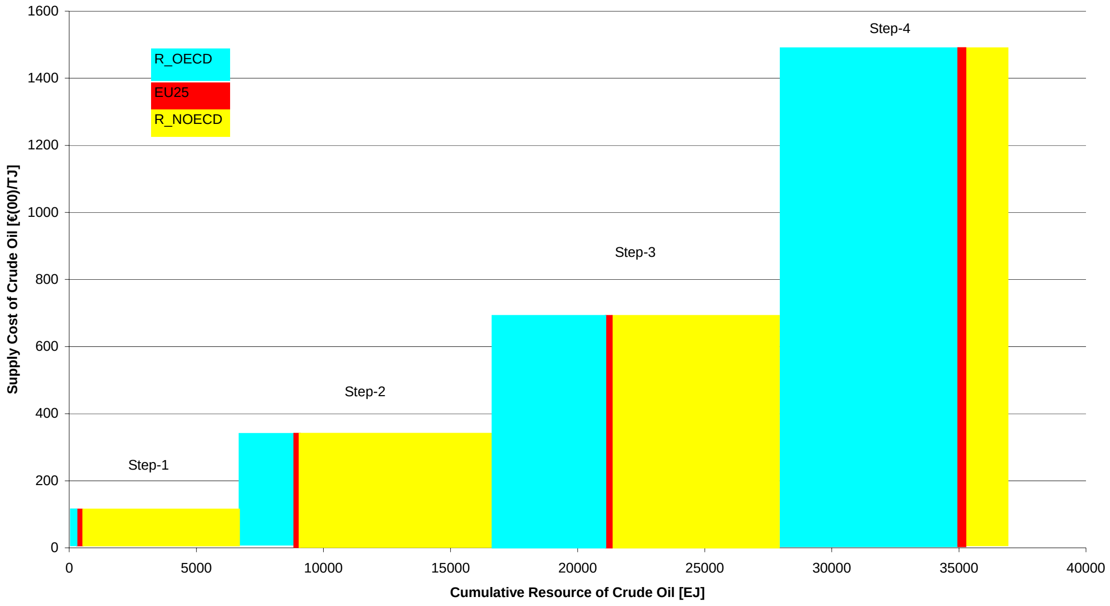


Figure 3-5: Supply-cost curve of crude oil with starting year 1990



3.2.4. Transport cost of energy carriers in inter regional exchange

The transport costs of energy carriers play a major role in a national and regional energy infrastructure development, in a future power generation framework as well as for emission strategies and national energy policy developments. Since transportation costs depend to a great extent on the distance of transportation, it is not certain that transportation costs will always be lower than the production costs of an energy carrier. For some energy carriers the costs of production is lower than it's cost of transportation depending on the distance covered for import a the energy carrier.

Table 3-3: Transport cost in (€(00)/GJ)

Unit Transportation Cost Crude Oil (€(00)/GJ)				
Regions		EU25	R_OECD	R_NOECD
	Cities	Rostock	New York	Santosh
EU25	Rostock		0.32	0.23
R_OECD	New York	0.32		0.19
R_NOECD	Santosh	0.23	0.19	
Unit Transportation Cost Natural Gas (€(00)/GJ)				
Regions		EU25	R_OECD	R_NOECD
	Cities	Rostock	New York	Santosh
EU25	Rostock		2.18	3.00
R_OECD	New York	2.18		4.08
R_NOECD	Santosh	3.00	4.08	
Unit Transportation Cost Hard Coal (€(00)/GJ)				
Regions		EU25	R_OECD	R_NOECD
	Cities	Rostock	New York	Santosh
EU25	Rostock		0.11	0.43
R_OECD	New York	0.11		0.14
R_NOECD	Santosh	0.43	0.14	

Sources: /SAUNER 2000/, /hm-usa/,/usembmal/

Internal regions generated in TIMES are interconnect by trading of energy carriers, in which one region can import or export energy carriers from other regions. The calculation of the transport costs for hard coal, natural gas and crude oil is based on the SAUNER transportation data and the distance between trading centres. Rostock, New York and Santosh are regarded as the trading centres for the regions EU25, R_OECD and R_NOECD respectively and the straight distance between two trading centres are taken as the length of transportation between them. The transport costs of crude oil and oil products are identical, whereas the transport cost of Liquefied Natural Gas (LNG) is 1/600th times of the natural gas due to it's higher density.

The transport costs for inter regional transport of goods and energy carriers have been modelled carefully inside the study. Even though there is still space for improvement, since the trading of a region is not confined at one place of a region. In reality it is rather diversified to locations inside a region. The whole world is divided into only three regions and therefore it is difficult to locate the trading centres within the dispersed regions. Thus, the calculation of transport costs is an approximation.

3.2.5. Climate model

The climate model represents the change of temperature within the different layers of the atmosphere and within ocean subject to the Greenhous Gas (GHG)- concentration. The climate model starts with an initial global emission generated by the model and proceeds to derive the changes in CO_2 concentrations in three reservoirs (atmosphere, biosphere, upper ocean layer, and lower ocean layer), the total change (in compared to pre-industrial times) in atmospheric radiative forcing from GHGs emission and the temperature changes (in compared to pre-industrial times) in two reservoirs (atmosphere, biosphere and upper ocean layer) /Loulou et al. 2005/. The climate equations used to perform the calculation are adopted from /Nordhaus and Boyer 1999/ who proposed linear recursive equations for the calculation of concentrations and temperature changes. The approach is simplified but still more accurate in compared to other studies. Yet it is does not include the conceptual or methodological aspect of a sea level rise.

Concentrations of CO_2 in the reservoirs

The equation of the concentration of CO_2 in atmosphere, biosphere+ocean surface and deep ocean is given below.

$$M_{atm}(t) = E(t-1) + \Phi_{11} M_{atm}(t-1) - \Phi_{12} M_{atm}(t-1) + \Phi_{21} M_{up}(t-1) \quad (1)$$

$$M_{up}(t) = \Phi_{22} M_{up}(t-1) + \Phi_{12} M_{atm}(t-1) - \Phi_{21} M_{up}(t-1) + \Phi_{32} M_{lo}(t-1) - \Phi_{23} M_{up}(t-1) \quad (2)$$

$$M_{lo}(t) = \Phi_{33} M_{lo}(t-1) - \Phi_{32} M_{lo}(t-1) + \Phi_{23} M_{up}(t-1) \quad (3)$$

Where:

$M_{at}, M_{up}, M_{lo}(t)$:	CO_2 accumulated (GtC) in atmosphere, in upper ocean layer and biosphere, and in lower ocean layer in year t
E (t):	CO_2 emissions in the previous year (GtC)
Φij:	transfer rate from reservoir i to j from year t-1 to t (*i, j = atm, up, lo*)

$M_{atm}(1990) = 735$ GtC $M_{up}(1990) = 781$ GtC

$M_{lo}(1990) = 19230$ GtC $M_{atm}(0) = 590$ GtC (pre-industrial value)

Radiative forcing

The relationship between GHG accumulations and increased change in radiative forcing (ΔF(t)), is derived from empirical measurements and climate models.

$$\Delta F(t) = \gamma * \frac{\ln(M_{atm}(t)/M_0)}{\ln 2} + O(t) \quad (4)$$

where,

M_0 (i.e. CO_2ATM_PRE_IND): reference pre-industrial (circa 1750) CO_2 concentration in the atmosphere = 596.4 GtC.

γ: radiative forcing sensitivity of climate to doubling of the atmospheric CO_2 concentration = 4.1 W/m^2.

O(t) (i.e. EXOFORCING(t)): increase in total radiative forcing (W/m^2) at period *t* relative to pre-industrial level due to anthropogenic GHG's not accounted in the computation of CO_2 emissions.

In the study of /Nordhaus and Boyer 1999/, only CO_2 emissions were explicitly modelled and other emissions (CH_4, SF6, N_2O, CO, CFCs, HFCs, PFCs, ozone, moisture and aerosols) which partly also belong to the GHG's, have not been considered.

Temperature change

The climate change is represented by the change in the global mean surface temperature. The two-reservoir model is considered from the rational point that a higher radiative forcing warms the atmospheric layer, which quickly warms the upper ocean layer. Thus, the upper ocean and atmosphere are combined to form one reservoir as the other reservoir is represented by the deep ocean layer.

$$\Delta T_{up}(y) = \Delta T_{up}(y-1) + \sigma_1\{ F(y) - \lambda\, \Delta T_{up}(y-1) - \sigma_2\, [\Delta T_{up}(y-1) - \Delta T_{low}(y-1)]\} \quad (5)$$

$$\Delta T_{low}(y) = \Delta T_{low}(y-1) + \sigma_3\, [\Delta T_{up}(y-1) - \Delta T_{low}(y-1)] \quad (6)$$

Where,

ΔTup = globally averaged surface temperature increase above pre-industrial level,

ΔTlow = deep-ocean temperature increase above pre-industrial level,

σ_1 = 1-year speed of adjustment parameter for atmospheric temperature,

σ_2 = coefficient of heat loss from atmosphere to deep oceans,

σ_3 = 1-year coefficient of heat gain by deep oceans,

λ = feedback parameter (climatic retroaction) (λ = 4.1/Cs, Cs being the temperature sensitivity to CO_2 concentration doubling).

The parameter Cs, which is the temperature sensitivity to CO_2 concentration doubling, is highly uncertain, and may range from 1°C to 10°C.

The atmospheric CO_2 concentration has changed from 280 ppmv in the pre-industrial level to 365 ppmv in the year 2000 and during this time the atmospheric temperature has changed around 0.6°C. The high and low estimation scenario by /Moore III et al. 2005/ predicts the temperature rise of world will be 0.5°C to 1°C till 2100, additional 2°C at 710 ppmv and 3.4°C at 1114 ppmv in the year 2200 and according to their model result, the rise of sea level will be around 10cm at 550 ppmv stabilisation in 2100 and towards 2300 it will rise to 20-30cm. Other studies also predict a temperature increase without mitigation policies of about 1.7°C to 4.9°C in the time interval of 1990-2100 /Wigley and Raper 2001/.

Input parameters of the climate model

Table 3-4 shows the assumed values of all parameters of the Climate Model except exogenous forcing.

Table 3-4: Parameters of the climatic model (default values as GAMS notation) *Note: Last six parameters are given for the year 1995 and the appropriate values must be provided for all milestone years.*

Parameter	**Default value**
Gamma	4.1 W/m^2
PHI_UP_AT	0.0453 per year
PHI_AT_UP	0.0495 per year
PHI_LO_UP	0.00053 per year
PHI_UP_LO	0.0146 per year
C_s not directly needed	2.91 °C
LAMBDA	1.41
SIGMA1	0.024 per year
SIGMA2	0.44 (no time dimension)
SIGMA3	0.002 per year
CO2ATM_PRE_IND	596.4 GtC (pre-industrial equilibrium)
CO2_ATM_0	735 GtC (in 1995)
CO2_UP_0	781 GtC (in 1995)
CO2_LO_0	19230 GtC (in 1995)
DELTAT_ATM_0	0.43 ^{o}C (1995)
DELTAT_LOW_0	0.06 ^{o}C (1995)
DELTAFORCING_0 not directly needed	1.0395 (1995)

The definition of the parameters are:

PHI_AT_UP, PHI_UP_AT, PHI_UP_LO, PHI_LO_UP (also denoted *φatm-up*, *φup-atm*, etc): annual CO$_2$ flow coefficients between the three reservoirs (AT = Atmosphere, UP = Upper ocean layer, LO = Deep ocean layer). These are time-independent coefficients and unit less.

CO$_2$ATM_0, CO$_2$UP_0, CO$_2$LOW_0: initial period (1995 by default) values of CO$_2$ in the atmosphere, the upper ocean layer, and the deep ocean layer, respectively and expressed in unit of GtC.

CO$_2$_AT_PRE_IND: pre-industrial atmospheric CO$_2$ concentration represented in unit of GtC.

GAMMA (also denoted γ: radiative forcing sensitivity to a doubling of the atmospheric CO$_2$ concentration and presented in Watts/m^2.

LAMBDA (also denoted λ: a feedback parameter, representing the equilibrium impact of CO$_2$ concentration doubling in climate. Cs being the temperature sensitivity to a doubling of CO$_2$ concentrations (^{o}C), and γ the radiative forcing sensitivity to CO$_2$ concentrations doubling (W/m^2), the parametric relation between them is $\lambda = \gamma/C_s$.

SIGMA1 (also denoted σ_1): speed of adjustment parameter for atmospheric temperature. $1/\sigma_1$ represents the thermal capacity of the atmospheric + upper ocean layer (W-yr/m^2/^{o}C).

SIGMA2 (also denoted σ_2): ratio of the thermal capacity of the deep oceans to the transfer rate from shallow to deep ocean (W/m^2/^{o}C).

SIGMA3 (also denoted $\sigma 3$): $1/\ \sigma 3$ is the transfer rate (per year) from the upper level of the ocean to the deep layer of ocean (yr^{-1}).

DT_ATM_0, DT_LOW_0: values in initial period (1995 by default) of the temperature changes (regarding to pre-industrial time) in atmosphere and deep layer, respectively (^{o}C).

EXOFOR(y): radiative forcing from Non-CO$_2$ gases in each year from 1995 with unit of Watts/m^2.

DT_FORC(t): the total change in forcing in period t (W/m2).

DT_TATM(t) and DT_TLOW(t): average global temperature changes in the atmosphere and in deep ocean respectively, in period t, relative to the average global temperatures in pre-industrial time and bears the unit of ^oC.

Nordhaus and Boyer used the following formula to calculate the radiative forcing due to all GHG's except CO_2. Within the TIMES global model, the energy related methane and N_2O emissions are already accounted in the calculation of CO_2 equivalent emissions. Therefore, the formula below constitutes an upper bound for the radiative forcing due to other gases.

$$\text{EXOFORCING}(t) = \begin{cases} -0.1965 + 0.013465 \times (m(t)-1995), & \text{if } 1995 <= m(t) <= 2095 \\ 1.15, & \text{if } m(t) > 2095 \end{cases}$$

In this climate model the temperature rise of the atmosphere has been considered. It is calculated and reported by the model for different study periods. The increase of the temperature is compared to the pre-industrial year 1750. The rise of temperature in the atmosphere is the phenomenon coming out of the radiative forcing, that is considered by different values from different studies. The study by Nordhaus and Boyer considered 4.1 W/m^2 /Nordhaus and Boyer 2001/ and Third Assessment Report by Working Group I provides a slightly smaller value of 3.7 W/m^2/ IPCC 2001/.

3.2.6. Two Factor Learning Curve (2FLC)

Learning concept

The process of learning is a mental and psychological phenomenon, which is natural, spontaneous and may be reflected as improvement of performance in terms of time, costs and knowledge /Barreto 2001/. The reduction of cost and time with respect to increase in production quantities is termed as learning effect in management science /Neij et al. 2000/ and its positive effect is realised by the improvement of knowledge (tacit), experience (skill) and performance.

Learning is indeed a key driver of techno-economic change, dissemination of technological innovation and performance improvement of any technology for a given activity. In technological dynamics, learning process plays a fundamental role in a technological landscape /Barreto 2001/ and states that the specific investment cost of any technology reduces with respect to knowledge accumulation through the deployment of capacity and R&D expenditure. Learning is a gradual process, accumulates with time and reinforces it's amplitude from past experience. It requires continuous action, and therefore future opportunities are strongly coupled to present activities. So continuous capacity deployment and R&D expenditures are required to maintain the consistency of the learning parameters /OECD/IEA 2000/.

Approach for TIMES within SAPIENTIA: Objective

Realising and understanding the influence of R&D expenditure on specific cost of immature technologies has drawn a lot of attention over many years. It has raised interest on all sides, starting from developers, investors and researchers. Researchers tried to trace back the influence of R&D on new technologies by the implementation of R&D expenditure as linear or mixed integer programming within a two factor learning approach.

Realization of two factor learning by MIP approach

The idea behind the two factor learning curve is that the R&D expenditure will be responsible for the specific cost reduction as given in Figure 3-6. So the R&D expenditure spent in the demonstration phase of any technology reduces the specific cost. The cost reduction is proportional to the correlation of cumulative capacity expenditure and the learning rate. The progress ratio of the technology is calculated by the correlation and a regression analysis and the factor is considered for the specific cost reduction by cumulative R&D expenditure. A stepwise reduction of specific investment was realised based on R&D expenditure structure. In analogue, the R&D expenditure is used for the production of fictive capacity, which does not add any value to the real cumulative capacity. The total cost (cumulative R&D expenditure and total cost from cumulative capacity), in relation to cumulative capacity (real and fictive) is given in Figure 3-7.

Figure 3-6: Impact of R&D expenditure on specific investment cost of any technology

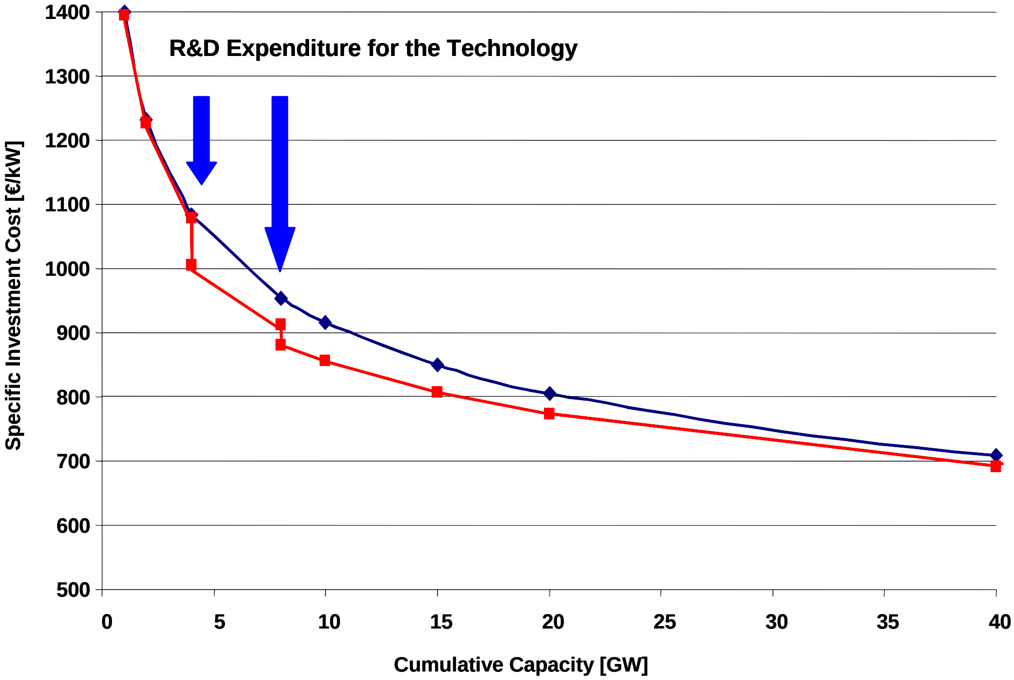
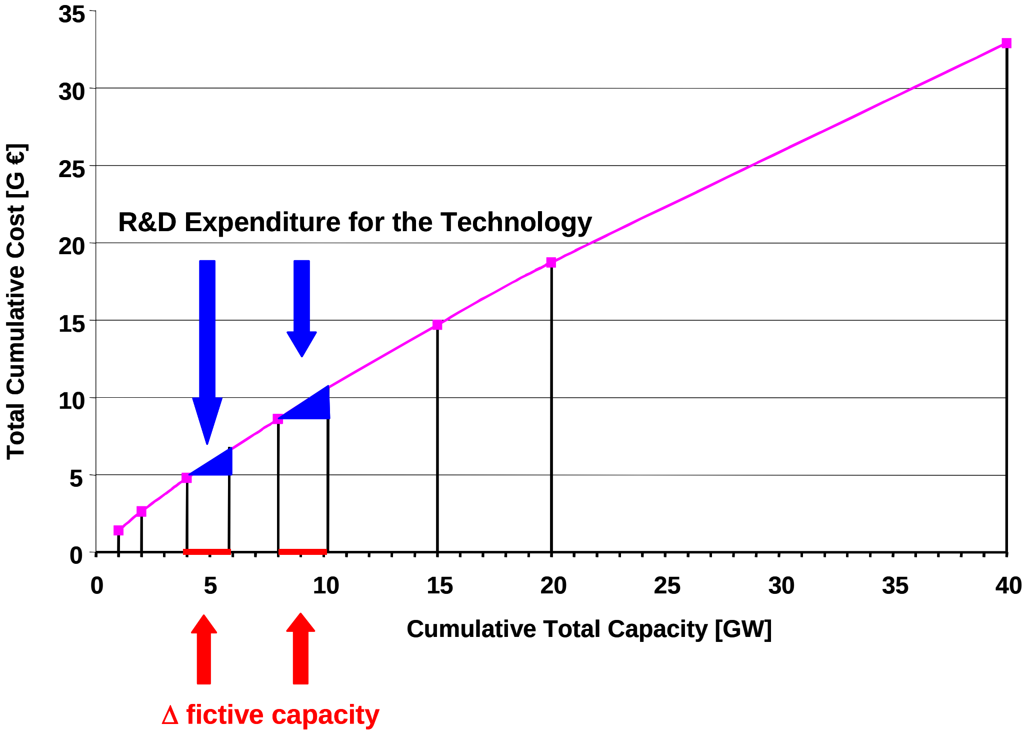


Figure 3-7: Impact of R&D expenditure on total cumulative cost of any technology



Analogous to single factor learning, the total cost (investment and R&D) in two factor learning are non-linear. Therefore, separable programming has been applied for the approximation of total cost. The non-convexity of the cost function is restricted by binary variable for global optima.

$$TC_{te,t} = \sum_{i=1}^{N} \alpha_{i,te} \cdot \delta_{te,i,t} + \beta_{i,te} \cdot \lambda_{te,i,t} \tag{6}$$

Correspondingly the total capacity by real capacity installation and the fictive capacity coming from R&D expenditure will be written in mathematical form.

$$C_{te,t} = C_{te,0} + \sum_{\tau=1}^{t} ncap_{te,\tau} + \sum_{\tau=1}^{t} ncap\_R\&D_{te,\tau} = \sum_{i=1}^{N} \lambda_{te,i,t} \tag{7}$$

Logical condition for convexification,

$$\sum_{i=1}^{N} \delta_{te,i,t} = 1 \tag{8}$$

$$\begin{aligned} \lambda_{te,i,t} &\geq C_{i,te} \cdot \delta_{te,i,t} \\ \lambda_{te,i,t} &\leq C_{i+1,te} \cdot \delta_{te,i,t} \end{aligned} \tag{9}$$

The fictive capacity depends on R&D expenditure of an individual technology or as a whole. If the R&D expenditures always induce constant fictive capacities, there will be a linear relation between fictive capacity and R&D expenditure. This implies that the efficiency of R&D expenditure over cumulative capacity decreases and worsens in compared to future demonstration projects. The assumption taken, that the efficiency of R&D expenditure concerning the learning rate for any technology remains constant, likewise the separable optimisation under consideration of binary convexification, has been taken.

$$C_{te,t-1} + \sum_{\tau=1}^{t} ncap\_R\&D_{te,\tau} = \sum_{i=1}^{N} \lambda R_{te,i,t} \tag{10}$$

Total cumulative R&D expenditure is written as:

$$TCR_{te,t} = \sum_{i=1}^{N} \alpha_{i,te} \cdot \delta R_{te,i,t} + \beta_{i,te} \cdot \lambda R_{i,te,t} \tag{11}$$

Logical condition for convexification,

$$\begin{aligned} \lambda R_{te,i,t} &\geq C_{i,te} \cdot \delta R_{te,i,t} \\ \lambda R_{te,i,t} &\leq C_{i+1,te} \cdot \delta R_{te,i,t} \end{aligned} \tag{12}$$

The R&D expenditure (R&DEte,t) for one technology te in model period t is,

$$R\&DE_{te,t} = R\&DI_{te,t} \cdot TCR_{te,t} - TC_{te,t-1} \tag{13}$$

The categorisation of R&D-Intensity for any technology can be expressed as,

$$\mathrm{R\&D\,I}_{\mathrm{te,t}} = \begin{cases} < 1 & \\ 1 & \text{Learning by doing} \\ > 1 & \end{cases}$$

The R&D Intensity is equal to 1 represents the investment in demonstration project. The R&D expenditure leads to an increase of the capacity and reduction of the investment cost. The philosophy behind the learning curve is that the cumulative capacity increases due to demonstration project. Following the respective learning rate reduces the specific investment cost. R&D intensity greater than one is desirable for the technology development and cost reduction. An intensity which is less than one can be achievable through demonstration projects.

The total amount of the R&D budget TR&DE can be restricted inside the model period-wise. The total R&D expenditure is mathematically described in equation 14.

$$TR\&DE = \sum_{te=1,\tau=1}^{N,T} R\&DE_{te,\tau} \tag{14}$$

The R&D expenditure basically consists of public and industrial R&D expenditures, which are hard to distinguish categorically. Also it is difficult to get the industrial R&D expenditure for single or group of technologies on a national and worldwide basis compared to government R&D. However it is comparatively easy to get data about public R&D because the government supports widely to the common research activities, whereas the industry works on its own benefit and the disclose of data may hamper their industrial products. The industrial R&D can be at least derived and approximated from the numbers of patents.

The two factor learning curve has been developed, implemented and tested in TIMES G3 model in order to understand the dynamical behaviour of technologies in the context of research and development expenditures' influence. Various scenarios have been formulated and tested inside the model. Details of the scenarios and their corresponding results are described in the following chapter.

4. MARKAL

This report describes the work undertaken with the Western European MARKAL database and model for the SAPIENTIA project.

4.1. The existing database

As a point of departure, the technology database describing the energy system for Western Europe was taken. This model describes the energy system of the fifteen pre-2004 EU countries, combined with Ice-land Norway and Switzerland. Apart for space heating, this region is treated as a single region, so with-out national boundaries or inter-country exchanges of commodities (energy, materials). Import in and exports out of the region are included for many fuels and materials. The region shares all technologies which do not have a geographic index, technologies are generic types (e.g. pulverized coal power plant, diesel car, residential gas boiler, electric arc furnace for steel making).

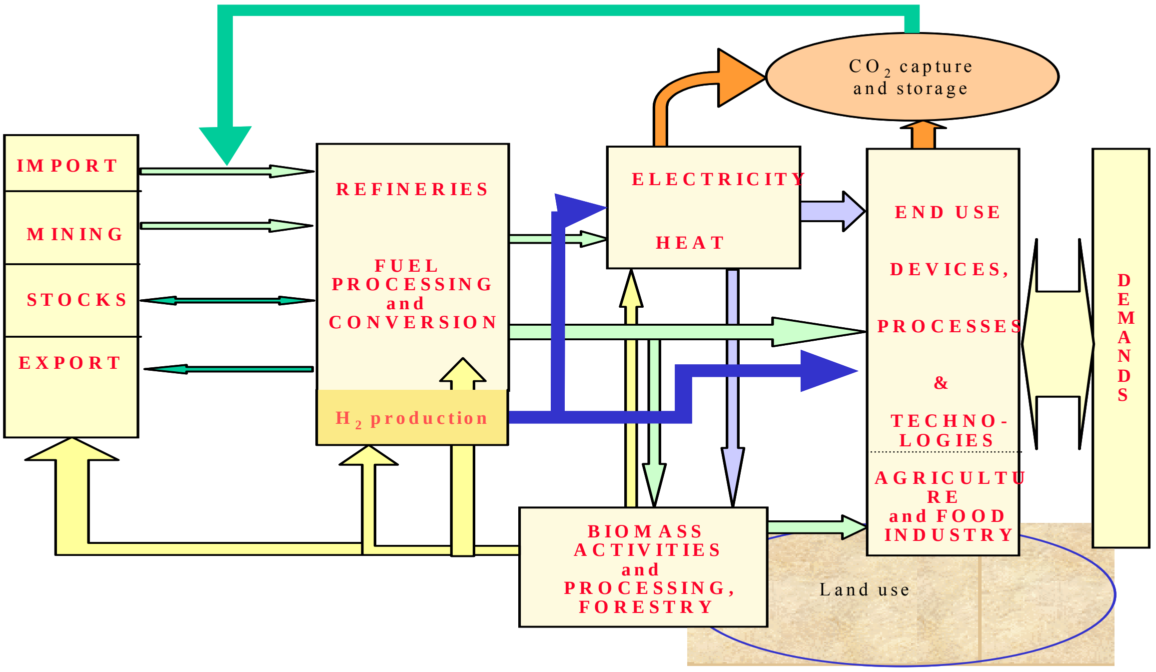
The model covers the 1990-2100 period in 10-year steps. Being a linear programming model, MARKAL optimizes, i.e. calculates the minimal total system cost, for the whole time period at once, i.e. it is ea model with perfect foresight. Being demand driven, MARKAL balances supply and demand of fuel in order to meet the exogenous determined demand levels for energy services (useful demand). These energy services are satisfied through end use technologies that consume fuel (final demand). This fuel is on its turn produced in conversion processes or directly supplied. The choice between competing technologies and fuels is based on their relative marginal costs, the model will choose those with the highest cost efficiency over their lifetime.

The end demands are attributed with a price-elasticity that allows them to differ from the input value under the effect of changing commodity prices. Commodity price changes are for instance induced by CO_2 constraints that will increase the internal price for fossil fuels. This mimics an actor behaviour and results in an estimate of the change of the producers and consumers surplus. This latter can be used as an approximation of the welfare loss under the given scenario assumptions.

Fuel use of fossil fuels leads to CO_2 emissions. These emissions are accounted for in the model on an overall level and for 7 sectors separately: agriculture, residential, commercial and service sector, trans-port sector, industry, conversion and the power sector. In addition to these the model accounts for emis-sion release and uptake for soils and forests, for emissions from specific industrial processes and for possible CO_2 capture and sequestration in geological formations.

An essential element in the MARKAL model used is the fact that it assumes perfect foresight about fu-ture events (taxes, emission constraints,…) and about technology availability. This may lead to antici-pating model choices in order to meet the set constraint or to minimise costs. Such a feature is instru-mental in the deployment of learning technologies, as the through the foresight the model can 'know' that initial additional investments will be compensated by future cost decreases.

Figure 4-1: Schematic overview of the MARKAL reference energy system



Technologies are characterized by a number of dedicated parameters depending on the classification of the technology (resource, conversion, process, end use demand). These parameters are both technical (efficiency, emission factors, fuel sue,…) as economic (lifetime, discount rate, investment and operation costs, …). Technology discount rates are added in addition to the overall discount rate for the sys-tem costs in order to include some actor investment behaviour and preferences.

The parameters have to be provided for all model periods, including the exogenous determined initial demand levels. This set of elements in the database, their definition and classification and the time series' values constitute the MARKAL model.

4.2. Technology change

Originally, MARKAL used exogenous determined trajectories for investment cost assumptions. These were based on scientific and engineering literature and on expert views concerning cost evolution. Given the perfect foresight of the model, some technologies needed to be constrained in their deploy-ment rate since otherwise the model could simply wait until a technology becomes competitive com-pared to the reference technology and alternatives, and then massively invest in the then cheaper tech-nology. As such a sudden change in profitability is generally unlikely, as the cost decrease implicitly assumes some deployment, growth limitations are required to enforce a more gradual phasing in of such technologies The specification of such limitations requires quite some expertise and manual interfer-ence in the model data. By doing so the modeler had a lot of influence on the behaviour of the model and on technology deployment paths.

Several sources [ref] indicated that a relationship could be observed between the development of the specific investment costs (investment per unit of capacity) and the cumulated capacity or sales build-up. This relationship describes the learning-by-doing, or learning-by-investing phenomena. Analysing the cost and capacity (or sales) data, a mathematical formulation in terms of a power law can be derived,

SCt = SC0 x (Ct/C0)-b

with PR= 2-b

where SCt = specific investment cost (e.g. €/kWe)

SC_0 = specific investment cost at t=0

C_t = cumulative capacity level at t

C_0 = cumulative capacity level at t=0

PR = progress ratio

The progress ratio is a measure on how fast a technology learns, i.e. it indicates the decrease in specific costs for each doubling of capacity. This means that by providing the initial values for capacity and in-vestment cost, and the progress ratio, the potential learning curve is completely defined. For modelling purposes this learning curve is then segment-wise linearised. For this segmentation, also the maximal achievable capacity has to be provided as model input data. As a consequence, the model can now decide itself on investment levels and timing, taking into account the corresponding investment cost development. This endogenises the investment costs.

Over the years and through different studies (TEEM, SAPIENT, PHOTEX, EXTOOL, ….) the number of technologies for which a learning curve has been estimated, and hence a learning formulation in the model could be implemented, increased gradually:

Table 4-1: Evolution of learning technologies in the ECN Western European Markal model

1997-1998	Solar PV, Wind turbine, Fuel Cell Car
1999	idem, Advanced coal, Natural gas combined cycle, Advanced nuclear, Solar thermal

At the time of the SAPIENT project, a further step in enhancing technological change was made [ref Ad]. This approach introduced the concept of technology clusters. Whereas in previous studies, a complete technology (e.g. solar PV or advanced coal) was learning, with the introduction of clustering technology spill over effects can be taken into account. Indeed each technology can be seen as being built up from a number of components (e.g. a natural gas combined cycle has a gas turbine, a recovery boiler and a steam turbine as principal elements). These elements or components are also found in other technologies. When the components are considered as learning this means that all technologies sharing these components benefit from the learning and at the same time also contribute to the experience or capacity build up.

The joint learning also leads to technology spill-over effects in different sectors of the energy system: e.g. a fuel cell component is found is stationary applications for electricity and heat production as well as in mobile application as vehicle engine.

Table 4-2: Evolution of number and kind of technology clusters in MARKAL

	clusters	# technologies involved	sectors involved
1999	fuel cell, gasifier, gas turbine, solar PV, wind turbine	28	power sector, transport
2002 (SAPIENT)	idem, hydro turbine, steam turbine, boiler, combined cycle boiler, nuclear reactor	59	power sector, transport
2004 (SAPIENTIA)	idem, CO_2 capture for coal (2) and gas (1); CO_2 storage injection; partial oxidation of coal; diesel, gasoline, electric and gas engine; oil and gas extraction (3); fusion reactor; gas steam reforming; residential boiler and condensing boiler; heat insulation; electrolyser; heat pump; advanced solar	354	power sector, transport, residential sector, commercial and service sector, industry, conversion sector

For the SAPIENTIA project, ample attention was given to possible learning and spill-over effects out-side the power sector. Prior to this project, the main focus had been on learning and cross-technology spill-over in the power sector. With the introduction of new learning components and with the enlargement of the cluster matrix involving more technologies, ECN contributed considerably to the extension of the modelling capacities in this project.

4.3. New learning components and extended cluster matrix

In addition to the already know learning components from the SAPIENT project (10 components, see Annex I for more details), mainly in the power sector, about 20 new learning components are added in the technology matrix. These components are shared among quite a large number of technologies in the database and across different sectors.

The following tables give an overview of the existing key components and how technology spill-over for them has been extended to the non-power sectors.

The first table gives an overview of the existing key components and the number of technologies involved. A single technology can belong to more than one cluster. An example is a natural gas combined cycle power plant which is found under gas turbine, combined cycle boiler and steam turbine.

Obviously, most of the existing cluster technologies were only found in the power sector, only fuel cells were also occuring outside the power sector, namely in transport. Now for SAPIENTIA, important and promising key components are introduced in technologies in the building sector (residential and commercial and service buildings) (fuel cells) and in industry (boilers). The use of fuel cells in transport has been expanded to more automotive technologies than in the previous project (SAPIENT). The inclusion of these non-power sector technologies in most case doubles the number of technologies in which the key component can build up capacity (experience) and hence can be able to reduce the specific costs for future investments.

In the modeling data, the necessary adjustment concerning initial capacity for boilers had to be included in order to:

- correct for the past industrial boiler experience;
- not to unjustly over-speed the learning (through capacity doublings) now that industrial boiler investments are included.

For fuel cells this adjustment was not necessary since there is no market deployment pre-1990.

Table 4-3: Existing SAPIENT key components and related technology spill-over

learning key component	**number of technologies and sectors involved in SAPIENT**	**number of technologies and sectors added in SAPIENTIA**
Boiler	16 in power sector	18 in industry
Combined cycle boiler	42 in power sector	-
Fuel cell	6 in power sector 4 in transport	8 in transport 11 in buildings
Gasifier	29 in power sector	-
Gas Turbine	48 in power sector	-
Hydro turbine	4 in power sector	-
Nuclear reactor	2 in power sector	-
Solar PV	6 in power sector	-
Steam turbine	69 in power sector	-
Wind turbine	8 in power sector	-

In addition to the extension of the coverage of the existing SAPIENT key components, also 20 new key components have been identified and successfully added in the WEU MARKAL model for SAPIENTIA. The results of this extension can be found in the following table where per key compo-nent the number of technologies is given and the sectors in which these technologies are found. Aside from increasing the number of learning components substantially, and consequently also the number of learning technologies, also the sectoral coverage is much broader: the fuel extraction and fuel conver-sion (in particular H_2 production), industry, transport and buildings now have many more competing technologies with learning components.

Table 4-4: New SAPIENTIA key components and technology spill-over

learning key component	number of technologies involved	sectors
Advanced solar	1	Power sector
CO_2 capture from coal fuel input	11	Power sector, fuel conversion (H_2)
CO_2 capture from coal fired flue gas	5	Power sector
CO_2 capture from gas fired flue gas	8	Power sector
CO_2 injection	6	Power sector, industry, fuel conversion (H_2)
Coal partial oxidation	2	Fuel conversion (H_2)
Diesel engine	13	Transport
Electric engine	14	Transport
Electrolyser	1	Fuel conversion (H_2)
FPSO (extraction)	3	Fuel extraction
Fusion reactor	2	Power sector
Gas engine	10	Power sector, transport
Gasoline engine	8	Transport
Gas steam methane reformer	2	Fuel conversion (H_2)
Heat Insulation	91	Buildings
Heat Pump	29	Buildings, industry
Platform (extraction)	6	Fuel extraction
Residential boiler	61	Buildings
Condensing gas boiler	49	Buildings
Subsea system (extraction)	6	Fuel extraction

Combining the existing components, the extension and the addition of the new ones, the total number of technologies affected by the 30 key components is well over the 300:

45 in transport
22 in industry
100 in the residential sector
69 in the commercial and service sector
9 in fuel extraction
6 for CO_2 storage
5 in fuel conversion
98 in the power sector

354 in total of which 236 in the end users' sectors and 118 in the supply sectors.

This means that roughly about 1/3 of all technologies in the WEU MARKAL database now are involved in technology spill-over. In the power sector specifically, all technologies have one or more learning components, also in the transport sector (comprising and spilt into cars, vans, buses, trucks) all technologies have the engine as learning component. The technologies involved contribute to and profit from learning at the same time. Technology spill-over is now clearly introduced and spread over more sectors.

The extensions being quite substantial, it should come as no surprise that problems concerning solvability of the problem might occur. Indeed, a model database with 30 key components, each have a linearised learning curve that exists of at least 10 segments, and having 13 time periods leads to about 400 integer variables. This is quite a rich structure, which clearly puts large challenges to the existing mixed-integer solvers (MIP). Tests confirmed that no optimal solution could be reached within a reasonable time frame (less than 24 hours computer processing (CPU) time) but only a solution within a certain tolerance range. It should be mentioned that also for an optimal solution, the default cut-off tolerance used by the solver software (GAMS and CPLEX) is 10-9 (relatively to the obtained objective value). The iterations stop when the solution does not change within this tolerance range.

In order to improve the performance of the problem solving, an alternative to the MARKAL paradigm cluster formulation was introduced. The new approach still allows for technology spill-over as the key component is now modeled as a commodity that enters each technology in the cluster at the moment of investment of the technology. The amount of the commodity entering corresponds to the investment level of the technology.

The key technology is remodeled as a commodity producing process that satisfies the demand for that commodity, a demand generated by the required investments in the cluster technologies per model period. The satisfaction of this demand contributes in its turn to the learning experience and is added to the cumulative capacity of the commodity producing key component process. The key component processes remain endogenous learning technologies (ETL). However, this approach shifts the bulk of the calculation efforts from the MIP solving to the LP (linear problem) solving, gaining some speed in solution time. This results in higher model performance and allows a lower tolerance level, but is not sufficient to reach an optimal solution within acceptable running times.

This alternative required some remodeling of a few parameters for the key components and the technologies, but a comparative analysis showed that there were no significant changes in the results. Some results changed somewhat due to the possible difference in lifetime between the key component as it was modeled previously (MIP-clusters) and the cluster technologies. This effect on the model results was small.

Another advantage of this material commodity approach, which is by the way the only existing manner to include ETL in a multi-region MARKAL model, is that when run as a LP problem, technology spill-over can be taken into account. The endogenous learning character of the technologies of course is lost for such an LP case, as the cost trajectory for the key components has to be estimated exogenously or based on existing results from a previous ETL analysis.

III. Extensions of the POLES World Model

Silvana MIMA and Patrick CRIQUI **LEPII-EPE**

1. Introduction

The interest for the identification of feasible strategies for the transition to cleaner and sustainable energy systems is constantly growing and it appears more and more clearly that new and decarbonised energy carriers will represent an essential dimension of any strategy, not only for emissions reductions but also for ensuring the necessary shift “away from oil”.

Hydrogen-energy and CO_2 Capture and Storage (CCS) are contemplated by many as the most promising options. But these technologies are not enough advanced and because of the large uncertainties on key parameters, the economics of hydrogen production and delivery and of CCS is very difficult to precisely establish today. However the competitiveness of Hydrogen-energy and CO_2 Capture and Storage relatively to other new energy technologies or improved existing technologies has to be fully explored for policy makers to decide the structure of long term energy R&D programmes. This is why it has been decided to introduce in the POLES model a full description of the key Hydrogen-energy and CO_2 Capture and Storage technologies, in the methodological perspective of the SAPIENTIA project, i.e. with Two Factor Learning Curves linking the technologies’ costs with cumulated experience and government or business R&D.

The introduction of this new energy technologies, which were considered as not being potentially significant for the medium-term horizon (2030) but much more important for a farther future, accompanied the extension of the time horizon (up to the 2050) of the detailed POLES model. In that perspective, the most important developments in the model have concentrated on the description of the hydrogen economy, the development of decentralised electricity generation, CO_2 Capture and Storage and the integration in POLES of the SAPIENTIA Two Factor Learning Curves with clustering effects.

The modelling of the hydrogen economy is presented in Section 2 and starts with the demand side. Hydrogen is supposed to be principally used through fuel-cells which have a better efficiency than conventional engines either in stationary or in mobile uses. However, in order to not exclude some possible niche-markets and technologies, thermal hydrogen vehicles are also considered as part of hydrogen demand. The way how the hydrogen demand is calculated is described in sections 2.1.1 and 2.1.2. A second important step for the presentation of the hydrogen economy in the POLES model has been the completion of the dataset characterizing the production technologies. Standardization of data collected from different studies has been necessary to provide a satisfactory description of the constant and variable costs of hydrogen production (see report on the TECHPOL database).

The corresponding supply to hydrogen demand is provided by a set of ten production technologies. The competition between these different routes in terms of production cost is described in section 2.1.3. While an often-mentioned target is to produce hydrogen only from renewable sources, in the short term these routes will be extremely expensive. Exceptions to this statement are niche-markets where surplus hydropower, for example, could be used to generate hydrogen at night, or in remote areas where conventional energy costs are high and hydrogen can act as an effective energy storage for intermittent renewable resources. Currently hydrogen can be produced most cheaply from fossil fuels but, in this case, CO_2 emissions will have to be taken into account, either directly or, when avoided with the cost of CO_2 Capture and Storage, through the cost of the corresponding equipments.

Section 3 is indeed dedicated to the description of the CCS technologies in the POLES model. Important uncertainties still hang over the long term sequestration of CO_2, the stability of the sequestration options, the available potential, the public awareness and acceptability. These issues will strongly impact the future development of CO_2 Capture and Storage, and determine if it will be a major or a marginal option. However the impact of these technologies is potentially very large and for that reason, the taking into account of the CCS in the SAPIENTIA-POLES model, on top of the hydrogen and electricity generation technologies can be considered as a major extension of the model. This extension is presented in this report, after a general overview of the CCS technologies and of the state of the art in geological storage potentials and CO_2 transportation options.

The integration of the SAPIENTIA Two Factor Learning Curves with clustering features, using NTUA proposition is presented in Section 4, in a synthetic way, with a set of graphs and diagrams illustrating the dynamics of the different technologies with endogenous learning.

The project has also benefited from other important novelties concerning the introduction of low emission technologies in the transport and building sectors, hydrogen transport and delivery costs. These new features have been introduced through activities in other research projects (respectively WETO-H_2 and CASCADE MINTS). The extension and revision of the key variables and parameters of the POLES model allows to produce a reference image of the world energy system to 2050, with the corresponding outcomes in terms of prices and demand for the key primary sources. The regional energy balances to that time horizon have also been produced and transmitted to the partners in SAPIENTIA.

2. Hydrogen Consumption and Production Module

2.1. Overview

A large part of total energy is used in small plants and vehicles, but it is expensive or even virtually impossible to collect the GHG emissions from them. In such situations, using hydrogen would avoid any emissions of greenhouse gases at the point of use.

Hydrogen is not a fuel, but an energy carrier, like electricity. It cannot be mined, drilled-for or cut down but must be manufactured from other compounds that are widely available on earth. The two most abundant hydrogen-containing compounds are water (H_2O) and hydrocarbon fuels (HxCy), such as oil or coal; biomass fuels, such as woodfuels or municipal wastes, are also a potential source of hydrogen. However, producing hydrogen from hydrocarbons yields CO_2 as a by-product and in that case ways of producing hydrogen without CO_2 are needed. Hydrogen can provide storage options for intermittent renewable technologies such as solar and wind, and, when combined with CCS technologies, can reduce the climate impacts of continued fossil fuel utilization.

This is why it is important to consider the complete processing chain for hydrogen production and use, in order to find out to what extent greenhouse gas emissions would fall with a substitution of hydrogen for other energy carriers. Many studies have been performed during recent years in order to address the complex subject of the “hydrogen economy”. Many of them have aimed at assessing the current state of technology for producing hydrogen from a variety of energy sources, the current and future projected costs, CO_2 emissions and efficiencies, infrastructure issues-with particular emphasis on light-duty vehicles in the transport sector.

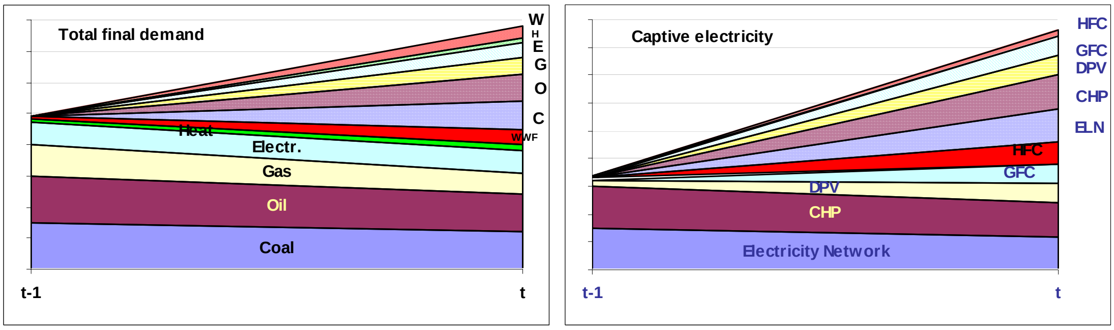
2.1.1. Hydrogen in stationary applications and the competition among distributed electricity generation options

The POLES model’s demand structure has been based on the distinction between substitutable fuels and specific electricity. For the very long-term it has been deemed important to introduce a full treatment of the competition among different distributed power generation technologies, including conventional cogeneration (CHP), Gas Fuel-Cells (GFC), Hydrogen Fuel-Cells (HFC), solar building-integrated panels (DPV).

CHP, GFC, HFC and DPV electricity production, which were part of the former New and Renewable module of POLES, now enter in competition with network electricity supply (ELN) in each final electricity consumption module. This competition is based on the standard mechanism that is used in the model for inter-fuel competition, i.e. on a set of standard equations that allow for a putty-clay type behaviour in the final energy markets substitution processes:

- the scraping of existing capacity allows to identify the need for new capacities in order to meet total demand,
- and for these new capacities only, the choice among competing options is based on the comparison of the full costs of the different options (see the following figure).

<u>Figure 2-1: Inter-technology substitution process</u>



The market shares for new capacities are computed through a set of Weybull functions on the basis of maturity coefficients (MT), which are endogenous and by themselves a function of the relative costs of the different options, network-based or distributed. Adjustment of the actual maturity factor to the theoretical one is simulated through a time-adjustment parameter that reflects time inertia in each market.

The endogenisation of base (theoretical) market shares (MTT) is performed in the following way:

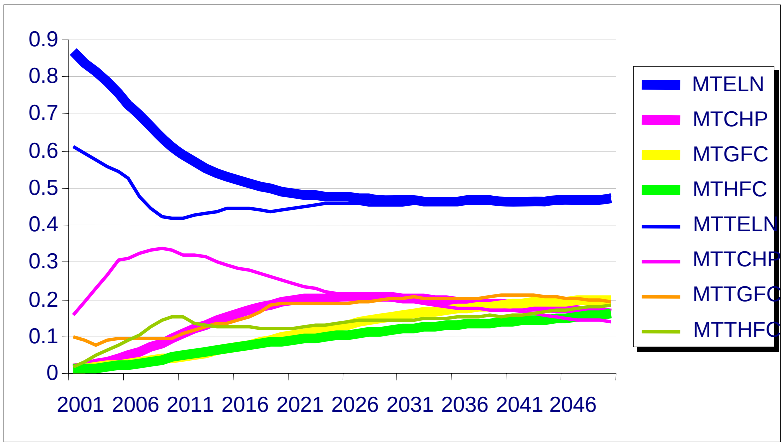
$$\mathrm{MTTi} = \frac{(\mathrm{CTi})^{\mathrm{EM}}}{\sum_{\mathrm{i}} (\mathrm{CTi})^{\mathrm{EM}}}$$

$$\mathrm{MTi} = \mathrm{MTi}_{-1} * \left(\frac{\mathrm{MTTi}}{\mathrm{MTi}_{-1}}\right)^{\mathrm{EAD}}$$

,where EAD is the time that is necessary for the effective market share to adjust to the base market share (typically EAD = 0.1 corresponding to 10 yrs of time adustment)

,where EM is the Weybull elasticity, an indicator of the degree of market diversity (i.e. the difference in market shares induced by a difference in the cost of two options, typically EM =-3). The figure below illustrates a simulation process for changes in the theoretical and adjustment in the effective market share:

Figure 2-2: Endogenised Base Market Share : theoretical and actual



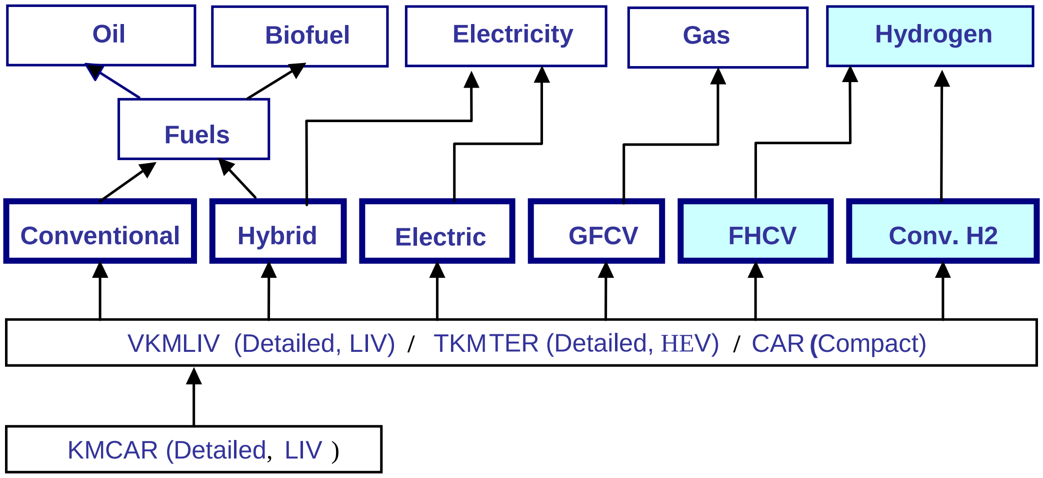
For those distributed electricity options that include cogeneration of heat and electricity (CHP, GFC and HFC), the value of the heat production from stationary fuel-cells and CHP is subtracted from the variable costs of the distributed electricity production.

This set of mechanisms allows in particular to derive the demand for hydrogen from stationary uses, which, combined with hydrogen for transport, builds the demand for hydrogen production, dealt with in a dedicated module.

2.1.2. Hydrogen in mobile applications

In the new version of POLES two kinds of mobile fuel-cells [one with hydrogen (HFCV) and one with methanol from natural gas (GFCV)] and one conventional direct hydrogen engine (THYV) are taken into account (extension of the transport module in WETO-H_2 project). The role of hydrogen in the POLES transport system is represented in the following figure:

Figure 2-3: New car concepts and transport fuels in POLES transport module



2.1.3. Hydrogen production system

Total Hydrogen production is endogenous and corresponds to sectoral demand (stationary and mobile fuel cells). As explained in the preceding section, the hydrogen demand from fuel-cells results from their competition with other options of distributed electricity on the one hand and with network electricity on the other hand.

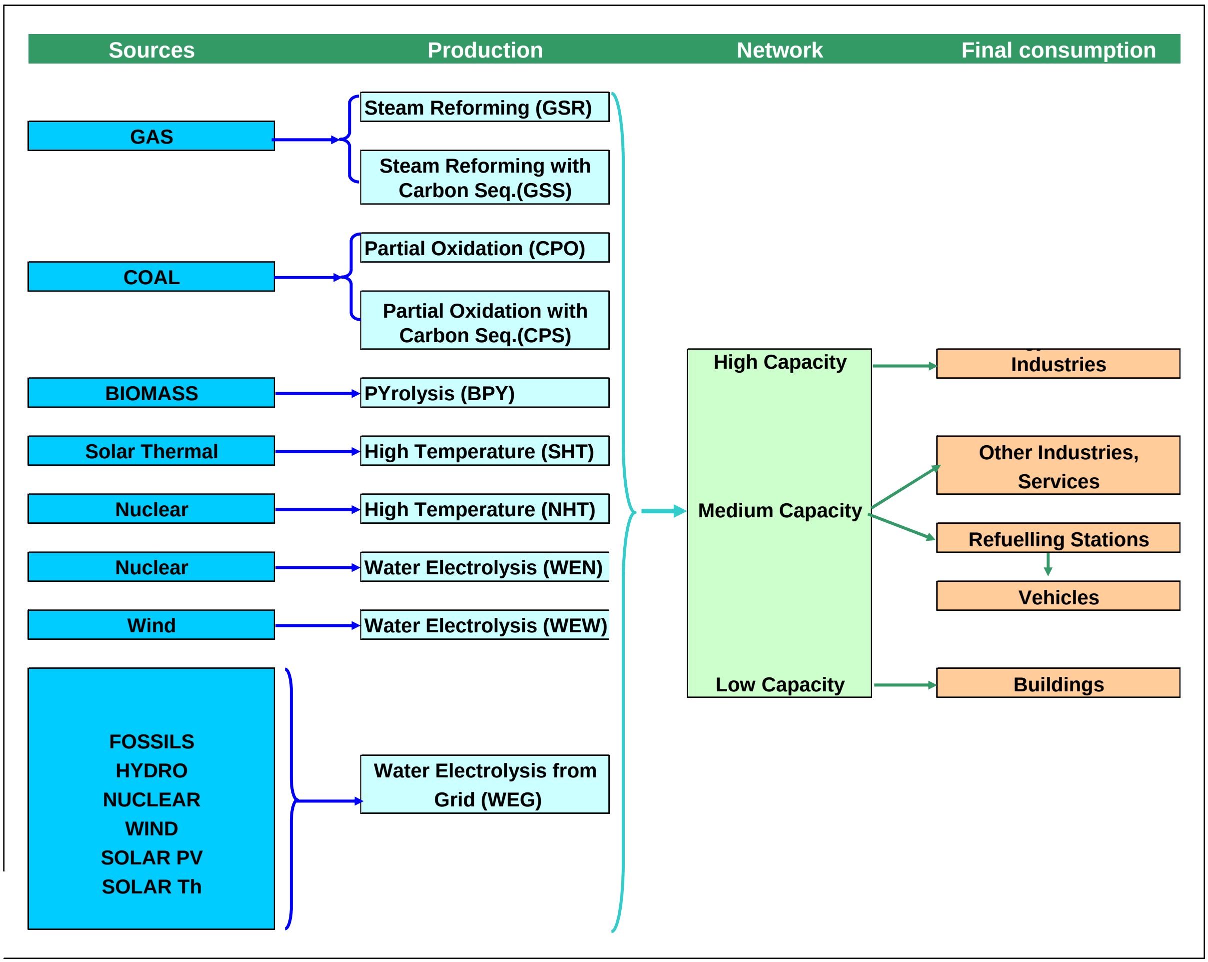
To fulfil the total Hydrogen demand, various options of hydrogen production have been identified. A large number of studies concerning hydrogen production have been scrutinized in order to choose the most representative and practical technologies to be included into the model. As a result ten Hydrogen production technologies have been selected :

Table 2-1: Hydrogen production technologies

Gas Steam Reforming	**GSR**
Gas Steam Reforming with CCS	**GSS**
Coal Partial Oxidation	**CPO**
Coal Partial Oxidation with CCS	**CPS**
Biomass PYrolysis	**BPY**
Solar thermal High-temperature Thermolysis	**SHT**
Nuclear thermal High-temperature Thermolysis	**NHT**
Water Electrolysis dedicated Nuclear power plant	**WEN**
Water Electrolysis dedicated Wind power plant	**WEW**
Water Electrolysis baseload electricity from Grid	**WEG**

The resulting description of the hydrogen economy in the POLES model is described in the following figure:

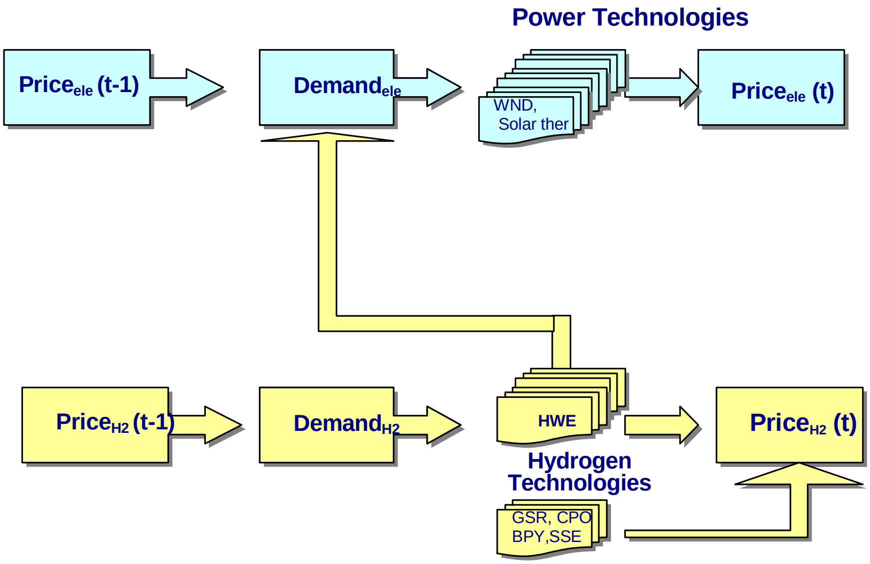
Figure 2-4: Structure of the Hydrogen module



The projected Hydrogen production capacities are endogenous to the model and are calculated for each year of simulation, on the basis of the relative investment and endogenous fuel costs: the investment costs by technology are endogenised through Two-Factor Learning Curves and the full-cost of each option, which is used for the planning of capacities also incorporates the costs of primary fuels

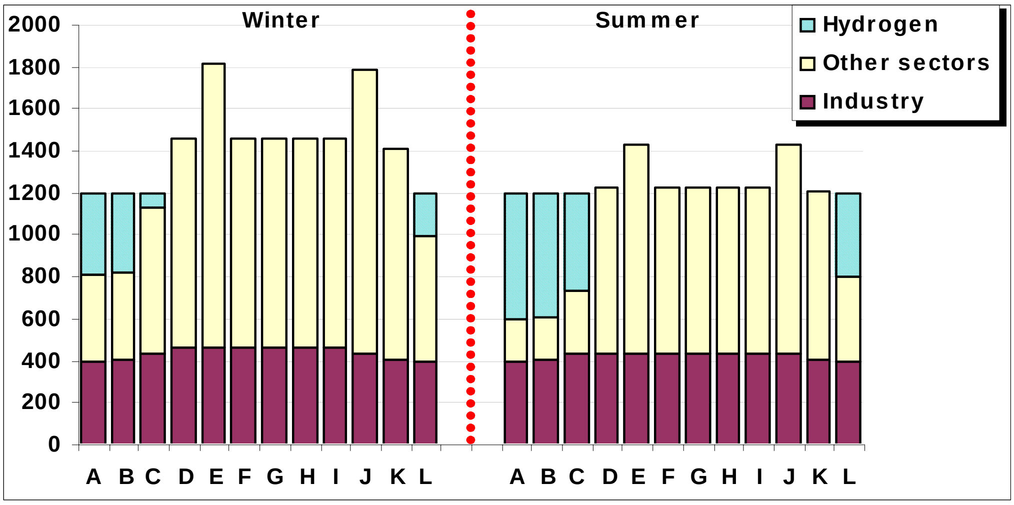
For each step in the simulation, once the available capacities are known from the preceding period's planned capacity, the distribution of production between the different technologies is operated while taking into account the plants variable costs, under the capacity constraint for the ten above-mentioned hydrogen plant categories. The share of each plant category depends on the variable cost (ACVCH), on the maturity factor for each technology (MTHYDR) and on a substitution parameter (EHHYDR). The production (HYDRTOT) is split by implicit equations and solving them iteratively according to market shares SHHYDR for different hydrogen plants.

Figure 2-5: Hydrogen and electricity production



The electricity demand for hydrogen production in electrolysis is connected to the electricity system with a taking into account of the load curve supposing that hydrogen is produced only with low cost off-peak electricity, as illustrated in Figure 2-6.

Figure 2-6: Load curve of electricity for industry, other sectors and for hydrogen production from HEW



After full simulation of the hydrogen production system, the fuel consumption of hydrogen plants is derived and added to the net final consumption of the different fuels. Applying the adequate loss or conversion coefficients to this total demand allows to calculate the total primary energy demand by fuel.

2.2. The modelling of hydrogen production technologies and uses

Technically the simulation of the hydrogen production encompasses the following steps:

- Total hydrogen production
- Available capacities for ten categories of hydrogen plants
- Hydrogen production by plant category
- Productions cost of the different plant categories and average full-costs for stationary and mobile demand
- Planning of new capacities (for following periods)
- Transport and delivery costs

2.2.1. Total hydrogen production

The total hydrogen production HYDRTOT is equal to the net demand of hydrogen NCHYDRTOT, divided by the transport-distribution loss factor RHYDRTD, minus the hydrogen international exchanges XMHYDR (with a positive sign if net imports) :

HYDRTOT[ALLC] = - XMHYDR[ALLC] (in ktoe)

The net demand of hydrogen is the sum of sectors' consumption (other industries, services, residential and transport for detailed countries and industry, residential-services and transport for compact countries):

NCHYDRTOT[DETAILED] = NCHYDR[DETAILED,OIN] + NCHYDR[DETAILED,SER] + NCHYDR[DETAILED,RES] + NCHYDR[DETAILED,RAT]

NCHYDRTOT[COMPACT] = NCHYDR[COMPACT,IND]+ NCHYDR[COMPACT,RSV] + NCHYDR[COMPACT,ROT] (in ktoe)

2.2.2. Installed and available capacities by hydrogen plant category

• ***Total available capacity***

For each of the above-mentioned ten hydrogen plant categories, the available capacity ACPWH [ALLC,HYDRPLANTS] increases of 1/10 of the new capacity identified in the preceding period for the year (t-1)+10. In case of decreasing capacities, a test guarantees that this decrease doesn't exceed the rate of phasing-out of existing capacities (which depends of the technical lifetime of equipment ACLTH[ALLC,HYDRPLANTS]).

$$\mathrm{ACPWH}_{[\mathrm{ALLC,HYDRPLANTS}]} = \mathrm{RESACPWH}_{[\mathrm{ALLC,HYDRPLANTS}]} +$$

$$\mathrm{IF\ ACPWH\ (-1)}_{[\mathrm{ALLC,HYDRPLANTS}]} + \frac{(\mathrm{EXPWH\ (-1)}_{[\mathrm{ALLC,HYDRPLANTS}]}) - \mathrm{ACPWH\ (-1)}_{[\mathrm{ALLC,HYDRPLANTS}]}}{10} >$$

$$\mathrm{ACPWH\ (-1)}_{[\mathrm{ALLC,HYDRPLANTS}]} *(1-\frac{1}{\mathrm{ACLTH}_{[\mathrm{ALLC,HYDRPLANTS}]}})$$

$$\mathrm{THEN\ \ ACPWH\ (-1)}_{[\mathrm{ALLC,HYDRPLANTS}]} + \frac{(\mathrm{EXPWH\ (-1)}_{[\mathrm{ALLC,HYDRPLANTS}]}) - \mathrm{ACPWH\ (-1)}_{[\mathrm{ALLC,HYDRPLANTS}]}}{10}$$

$$\mathrm{ELSE\ ACPWH(-1)}_{[\mathrm{ALLC,HYDRPLANTS}]} *(1-\frac{1}{\mathrm{ACLTH}_{[\mathrm{ALLC,HYDRPLANTS}]}}) \qquad (\mathrm{in\ Gm^3d})$$

- ***Total installed capacity***

For each plant category, the installed capacity (ACIPH) is the available capacity divided by the availability factor (ACAFH) :

$$ACIPH_{[ALLC,HYDRPLANTS]} = \frac{ACPWH_{[ALLC,HYDRPLANTS]}}{ACAFH_{[ALLC,HYDRPLANTS]}} \qquad \text{(in Gm}^3\text{d)}$$

Possible hydrogen production with existing installed capacities by plant category:

$APH_{2[ALLC,HYDRPLANTS]} = ACIPH_{[ALLC,HYDRPLANTS]} * 256.8 * 365 * ACAFH_{[ALLC,HYDRPLANTS]}$
(in ktoe)

2.2.3. Hydrogen production cost, by plant category

- ***Fixed costs*** *(ACFCH) by type of plant*

The fixed cost is the sum of the investment costs (ACINH), discounted on the economic life-time (ACETH) of the plant, and of the fixed O&M costs (ACFOH)

$$ACFCH_{[ALLC,HYDRPLANTS]} = \left(\frac{ACINH_{[ALLC,HYDRPLANTS]}}{\frac{(1+DISR)^{ACETH_{[ALLC,HYDRPLANTS]}}}{DISR\ *(1+DISR)^{ACETH_{[ALLC,HYDRPLANTS]}}}} + ACFOH_{[ALLC,HYDRPLANTS]} \right) / 257 * 1e+006$$

(in €99/toe/yr)

- ***Variable production costs*** *(ACVCH)*

The price of each fuel used for hydrogen productions in GSR, GSS, CPO, CPS is derived from the price of the corresponding fuel in industry; for the GSR and the CPO the CO_2 penalty is taken at full rate, while for GSS and CPS a correction is introduced to reduce carbon taxes for the part concerning the carbon sequestration as explained below in the description of the CCS module :

$CPSGAS_{[ALLC,INDUS]} = ETGAS_{[ALLC,INDUS]} + CPSGAS(-1)_{[ALLC,INDUS,PPTWELF1]} – ETGAS(-1)_{[ALLC,INDUS]} + VTGAS_{[ALLC,INDUS]} * (CPIMPGAS_{[ALLC]} – CPIMPGAS(-1)_{[ALLC]})$

$CPHYDR_{[ALLC,GAS]} = RESCPELE_{[ALLC,GAS]} + ETGAS_{[ALLC,POWERG]} * (1-KSGASH_{[ALLC,GSS]}) – ETGAS_{[ALLC,INDUS]} + CPSGAS_{[ALLC,INDUS]}$

$CPSCOAL_{[IMPCOALA,INDUS]} = ETCOAL_{[IMPCOALA,INDUS]} + RESCPSCOAL_{[IMPCOALA,INDUS]} + CPSCOAL(-1)_{[IMPCOALA,INDUS,PPTWELF1]} – ETCOAL(-1)_{[IMPCOALA,INDUS]} + VTCOAL_{[IMPCOALA,INDUS]} * (CPIMPCOAL_{[IMPCOALA]} – CPIMPCOAL(-1)_{[IMPCOALA]})$

$CPHYDR_{[ALLC,COAL]} = RESCPHYDR_{[ALLC,COAL]} + ETCOAL_{[ALLC,POWERG]}*(1-KSCOALH_{[ALLC,CPO]}) + ETCOAL_{[ALLC,POWERG]} * (1-KSCOALH_{[ALLC,CPS]}) – ETCOAL_{[ALLC,INDUS]}) + CPSCOAL_{[ALLC,INDUS]}$

For the biomass pyrolysis technology (BPY) the biomass cost that is taken into account is the cost of biomass used in BGT, with an adjustment factor:

$CPBPYH_2[ALLC] =RESCPBPYH_2[ALLC]+CST[ALLC,BGT]$

For water electrolysis from a dedicated nuclear plant (WEN) the cost of electricity is derived from power generation costs in a new power plant:

PRODCOST[ALLC,NND,d8030] = + ACVC[ALLC, NND] *1000/0.086

For water electrolysis from grid electricity (WEG) the cost of electricity is derived from baseload electricity price:

$CPELEH_2[ALLC] = RESCPELEH_2[ALLC]+CPBLDELE(-1)[ALLC,PPFIVE1]*1000/0.086$
(in €99/toe)

Then for each type of plant, the variable cost (ACVCH[ALLC,HYDROPLANTS]) is the sum of the variable O&M cost (ACVOH) and of the fuel cost. These fuel costs are the fuel price in €99/toe adjusted for the reference efficiency of the corresponding plant (ACEFH).

$$\mathrm{ACVCH}_{[\mathrm{ALLC,GSR}]} = \mathrm{RESACVCH}_{[\mathrm{ALLC,GSR}]} + \mathrm{ACVOH}_{[\mathrm{ALLC,GSR}]} + \frac{\mathrm{CPSGAS}_{[\mathrm{ALLC,INDUS}]}}{\mathrm{ACEFH}_{[\mathrm{ALLC,GSR}]}}$$

$$\mathrm{ACVCH}_{[\mathrm{ALLC,GSS}]} = (\mathrm{RESACVCH}_{[\mathrm{ALLC,GSS}]} + \mathrm{ACVOH}_{[\mathrm{ALLC,GSS}]} + \frac{\mathrm{CPHYDR}_{[\mathrm{ALLC,GAS}]}}{\mathrm{ACEFH}_{[\mathrm{ALLC,GSS}]}}) * \left(\frac{\mathrm{LIMST}_{[\mathrm{ALLC}]}}{\mathrm{LIMST}_{[\mathrm{ALLC}]} - \mathrm{CUMST}_{[\mathrm{ALLC}]}}\right)^{\mathrm{ELST}_{[\mathrm{ALLC}]}}$$

$$\mathrm{ACVCH}_{[\mathrm{ALLC,CPO}]} = (\mathrm{RESACVCH}_{[\mathrm{ALLC,CPO}]} + \mathrm{ACVOH}_{[\mathrm{ALLC,CPO}]} + \frac{\mathrm{CPSCOAL}_{[\mathrm{ALLC,INDUS}]}}{\mathrm{ACEFH}_{[\mathrm{ALLC,CPO}]}}$$

$$\mathrm{ACVCH}_{[\mathrm{ALLC,CPS}]} = (\mathrm{RESACVCH}_{[\mathrm{ALLC,CPS}]} + \mathrm{ACVOH}_{[\mathrm{ALLC,CPS}]} + \frac{\mathrm{CPHYDR}_{[\mathrm{ALLC,COAL}]}}{\mathrm{ACEFH}_{[\mathrm{ALLC,CPS}]}} * \left(\frac{\mathrm{LIMST}_{[\mathrm{ALLC}]}}{\mathrm{LIMST}_{[\mathrm{ALLC}]} - \mathrm{CUMST}_{[\mathrm{ALLC}]}}\right)^{\mathrm{ELST}_{[\mathrm{ALLC}]}}$$

$$\mathrm{ACVCH}_{[\mathrm{ALLC,BPY}]} = \mathrm{RESACVCH}_{[\mathrm{ALLC,BPY}]} + \mathrm{ACVOH}_{[\mathrm{ALLC,BPY}]} + \frac{\mathrm{CPBPYH2}_{[\mathrm{ALLC}]}}{\mathrm{ACEFH}_{[\mathrm{ALLC,BPY}]}}$$

$$\mathrm{ACVCH}_{[\mathrm{ALLC,SHT}]} = \mathrm{RESACVCH}_{[\mathrm{ALLC,SHT}]} + \mathrm{ACVOH}_{[\mathrm{ALLC,SHT}]} + \frac{\mathrm{CPHEAH2}[_{[\mathrm{ALLC}]}}{\mathrm{ACEFH}_{[\mathrm{ALLC,SHT}]}}$$

$$\mathrm{ACVCH}_{[\mathrm{ALLC,NHT}]} = \mathrm{RESACVCH}_{[\mathrm{ALLC,NHT}]} + \mathrm{ACVOH}_{[\mathrm{ALLC,NHT}]} + \frac{\mathrm{CPHEAH2}[_{[\mathrm{ALLC}]}}{\mathrm{ACEFH}_{[\mathrm{ALLC,NHT}]}}$$

$$\mathrm{ACVCH}_{[\mathrm{ALLC,WEN}]} = \mathrm{RESACVCH}_{[\mathrm{ALLC,WEN}]} + \mathrm{ACVOH}_{[\mathrm{ALLC,WEN}]} + \frac{\mathrm{PRODCOST}_{[\mathrm{ALLC,NND,d8030}]} * 1000}{0.086 * \mathrm{ACEFH}_{[\mathrm{ALLC,WEN}]}}$$

$$\mathrm{ACVCH}_{[\mathrm{ALLC,WEG}]} = \mathrm{RESACVCH}_{[\mathrm{ALLC,WEG}]} + \mathrm{ACVOH}_{[\mathrm{ALLC,WEG}]} + \frac{\mathrm{CPELEH2}_{[\mathrm{ALLC}]}}{\mathrm{ACEFH}_{[\mathrm{ALLC,WEG}]}} \qquad \text{(in €99/toe)}$$

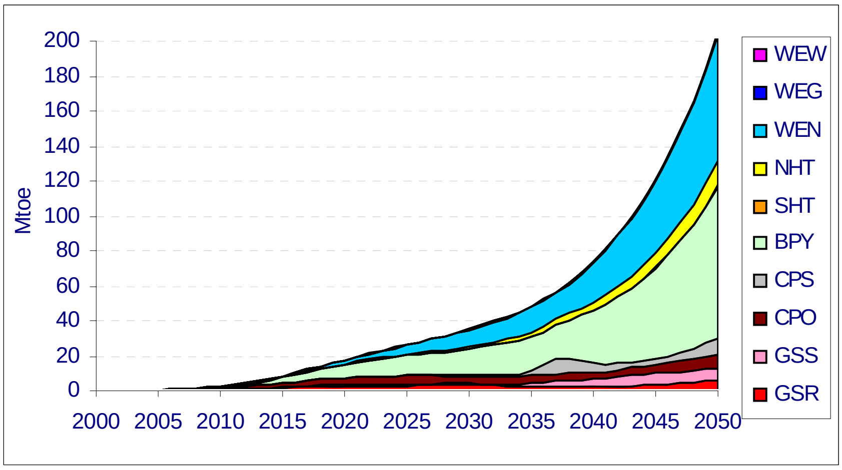
- ***Production costs** (PRODCOSTH)*

PRODCOSTH[ALLC,HYDRPLANTS] = + ACVCH[ALLC,HYDRPLANTS] (in €99/toe)

2.3. Illustrative results

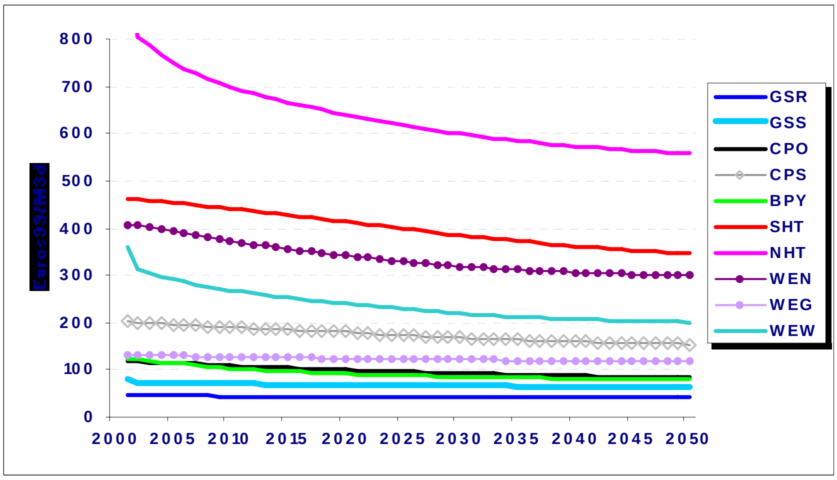
Hydrogen production ends at 200 Mtoe in the current SAPIENTIA-ref case (Figure 2-7). BPY and WEN dominate this production, while hydrogen production with sequestration represents 8% in 2050.

Figure 2-7: World hydrogen production by Technology



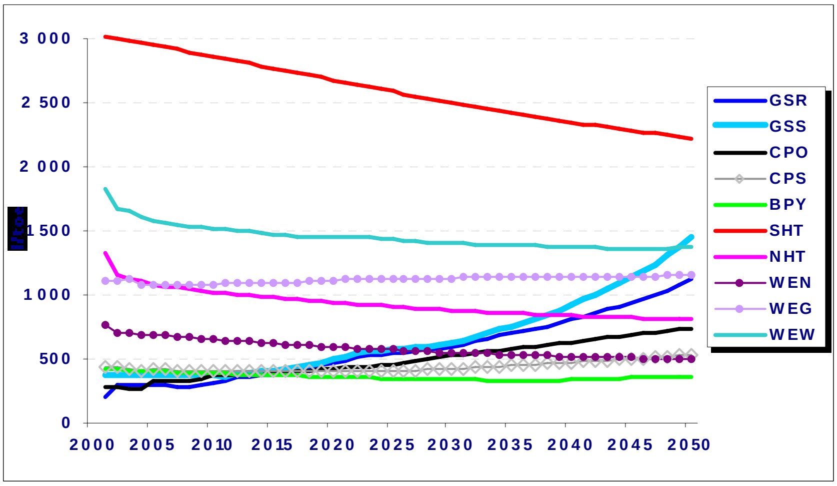
These results translate the combined impacts of the dynamics of investment costs on new installed capacities and of the production costs of the different technologies in competition to satisfy the total hydrogen demand. Thus, Figure 2-8 presents the investment costs which define the order of merit for the construction of the new capacities. GSR, GSS, BPY, CPO, WEG and CPS have the lowest investment cost and therefore better development prospects.

Figure 2-8: Investment Costs for key hydrogen production technologies



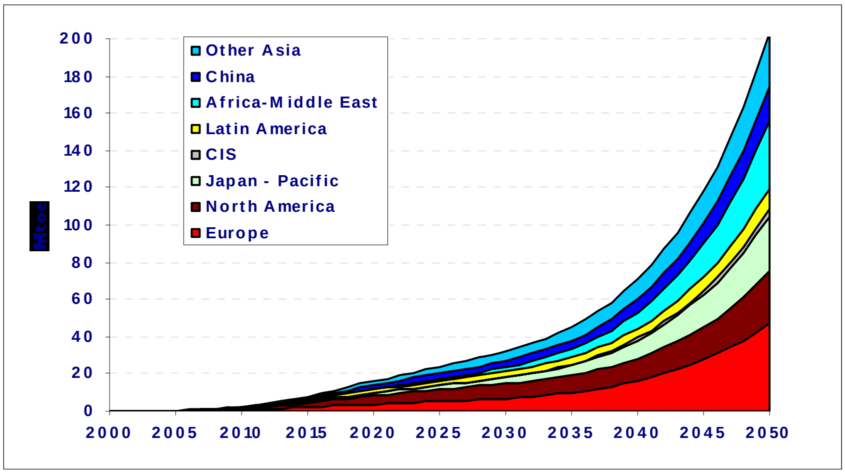
The order of merit also changes for the comparison of the production costs because of the increase of the fuel prices. BPY, CPS and WEN have the lowest production cost in the long run. Although GSR initially shows the lowest investment cost, because of the increase of the gas price its production cost at the end of the period is higher than the one of all other technologies except solar high temperature.

Figure 2-9: Production Costs for key hydrogen production technologies



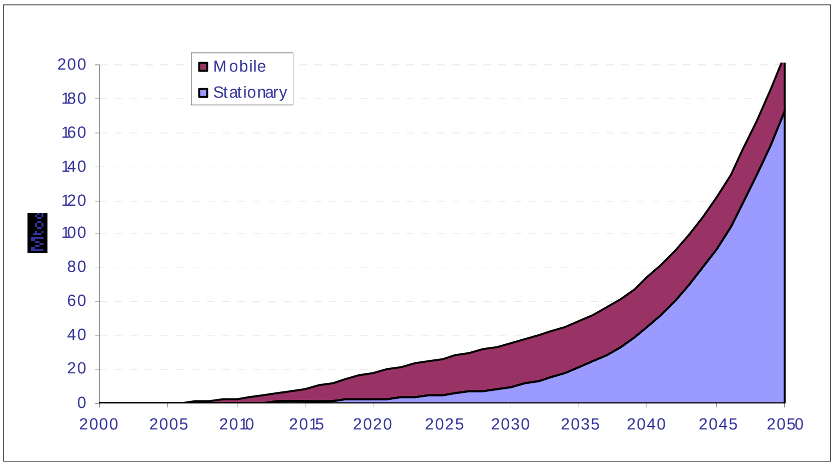
Hydrogen production has a relatively balanced profile across the regions. However Europe is the most advanced region in this set of results, representing nearly a quarter of the total production at the end of the period.

Figure 2-10: Hydrogen production by region



In terms of markets, most hydrogen demand comes from the stationary uses. Given the high level of the fuel-cell costs at the end of the period (495 €/kW), it is understandable that stationary uses became competitive earlier than mobile uses. For the same reason most hydrogen transport-fuel is used in the internal combustion engine hydrogen vehicles.

Figure 2-11: Hydrogen markets



3. Carbon Capture and Sequestration (CCS)

3.1. Overview

Carbon capture and storage (CCS) technologies remove carbon dioxide from flue gases and store them in geologic formations or in the ocean. This creates the possibility to produce power or hydrogen without releasing CO_2 into the atmosphere. That's why CCS is considered seriously in POLES as an option for addressing climate change policies, alongside with energy efficiency and carbon-free energy. Currently CO_2 sequestration strategies offer rather expensive and ecologically uncertain solutions, but in the longer term, the increasing environmental pressure combined with improved technologies and economic incentives may speed the CO_2 sequestration, also providing a stepping-stone to a hydrogen economy.

In the short and medium term, this option is likely to be less expensive than the use of renewable energy to produce hydrogen via electrolysis, while offering a comparatively soft transition from the current dependence on fossil fuels. Moreover, when CO_2 can be put to use as part of an enhanced oil recovery scheme (EOR), the net costs would be even less.

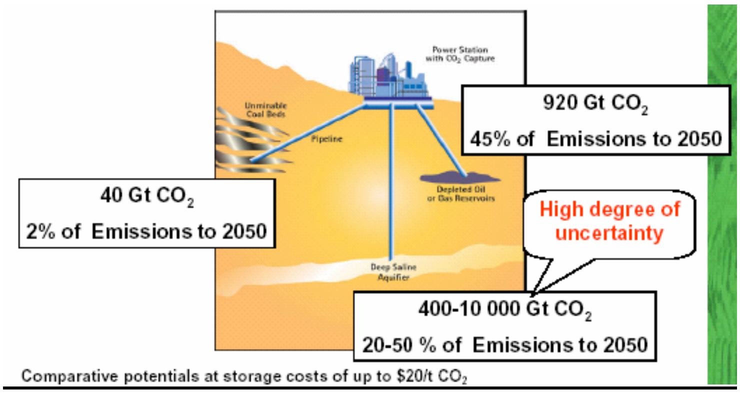
Storage in depleted oil and gas reservoirs represents the best near term option for application of CCS technologies. These sites have already demonstrated their ability to store pressurized fluids for millions of years, and knowledge gained during exploration for oil and gas has led to a relatively good understanding of the formations. There is little experience with CO_2 sequestration technologies other than EOR. Deep aquifers may also provide an attractive longer-term storage option if the feasibility and durability of the solution is further demonstrated, whereas ocean storage poses still greater technical and environmental uncertainty. Work to improve knowledge on these options is in progress.

According to Institut Français du Pétrole total estimated capacities of storage fields is of:

- more than 15 Gt in unexploited coal mines;
- 920 Gt CO_2 for depleted hydrocarbon fields;
- and 400-10000 Gt CO_2 in deep saline cavities.

Figure 3-1, although more optimistic for coal seems, confirms these assessments. Other geological storage schemes are under development and these “theoretical potentials" are likely to be reassessed in the future.

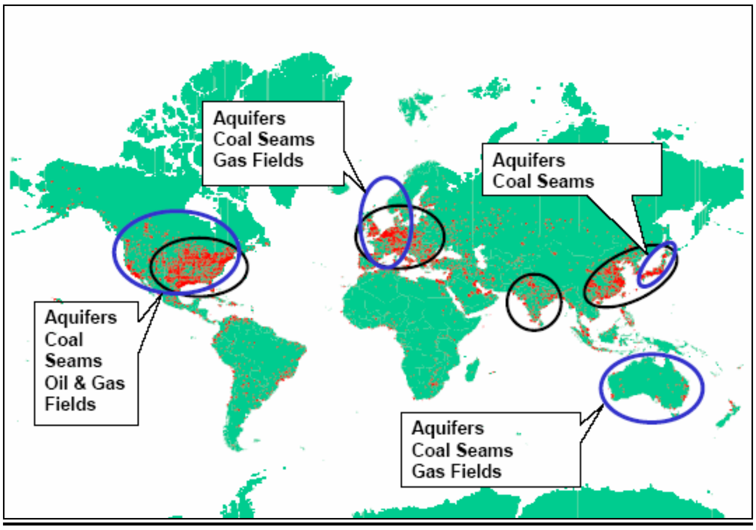
Figure 3-1: Geological Storage Potential : Global Storage Potential



Source : ftp://ftp.ecn.nl/pub/www/library/conf/ipcc02/ccs02-jg.pdf

Some studies try to compare geographically the main emission sources in the regions with high potentials for geological storage sites and they investigate the need for pipeline infrastructure networks in the most important regions to maximise the ‘realisable’ storage potential that can be achieved and the likely network costs. The following figure presents a general overview of this relationship in main regions around the world.

Figure 3-2: Regional CO_2 Emissions and Storage Potential



Source: John Gale (2002)

However, environmental risks do exist, including potential leakages of CO_2 through natural pathways or fractures caused by injection into geologic formations with possible contamination of groundwater. Leakage from surface installations and wells is also possible, though experience from EOR has demonstrated that these risks can be mitigated through quality construction, maintenance, operation, and control of storage facilities (Adams et al. 1994). In these conditions public acceptability of CCS remains however uncertain as long as the knowledge of the CO_2 behaviour in the vicinity of the region of injection is not confirmed or verified through experiments.

The cost for CCS can be split into, the cost of capturing CO_2 and the cost of storage, the modelling of which is presented in the following sections.

3.1.1. The cost of CO_2 Capture

CO_2 capture has been applied successfully for decades in the production of ammonia and other sectors. Several commercial CO_2 capture plants were constructed in the US in the late 1970's and early 1980's (Kaplan 1982; Pauley, Simiskey et al. 1984). Some of these plants are still in operation today. According to Institut Français du Pétrole the cost of capture represents between 50-75% of the total sequestration cost chain, depending on the type of fossil energy and on the technology used for electricity or hydrogen production. The papers that have addressed this issue (Gielen, 2003) provide costs varying from \$200 to \$250 per ton of carbon, i.e. 40 to 55 €/tCO_2.

3.1.2. The cost of CO_2 storage

The cost of storage includes the cost of compression, transportation and injection. These costs depend on many drivers, which varies from country to country and according to the types of storage reservoirs.

CO_2 is largely inert and easily handled. It is already transported in high pressure pipelines networks operating in North America, with limited safety/environmental problems. Although it is noted that these pipelines are routed in sparsely populated regions of the USA and Canada. Currently, there are some 3100 km of large CO_2 pipelines in operation, which have a capacity of 44.7 Mt/yr of CO_2, most of which are in the USA. Average costs of pipeline transport range from 2 to 6 €/tonne of CO_2 (Ecofys & TNO-NITG, 2002).

These pipelines supply CO_2 for enhanced oil recovery (EOR) operations and many have been operating since the early 1980s. To put these numbers in perspective, there are some 536 000 km of major natural gas transmission pipelines in the USA. The CO_2 pipeline network is substantial, but not that big in comparison with the amounts of other gases that are already being transmitted. New networks of CO_2 pipelines are now being considered in other regions of the world. In the

North Sea, a project called CENS lead by ELSAM and Kinder Morgan (an operator of CO_2 pipelines in the USA) is planning to establish a CO_2 pipeline network linking power plants in Denmark, Norway and the UK to offshore oil fields. The network would connect ten power plants with twelve oil fields over a period of eight years and would supply some 700 million tonnes of CO_2 for CO_2 EOR operations. The pipeline network will comprise 1500 km of CO_2 pipelines offshore together with 900 km onshore in Denmark and the UK. The project aims to take advantage of a window of opportunity for CO_2 EOR in the North Sea that could extend oil and gas production in the North Sea by some 15 years or more, assuming the economic situation is favourable to the oil producers.

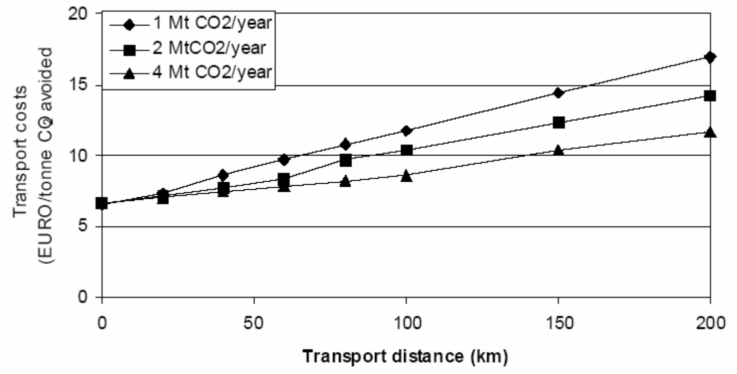
The compression and transportation costs

Carbon dioxide needs to be compressed to 8 MPa before transport. The compression costs amounts to 6 to 10 €/tonne CO_2 (Ecofys & TNO-NITG, 2002). The electricity that is needed for compression determines about half of the compression costs.

Transportation costs depend on the distance, type of transport (pipelines, tank wagons or ships) and the amount of CO_2 being shipped, ranging from 1 to 10 \$/tCO_2. Because of the huge volumes involved, only pipelines and ships are cost-effective options. Transport by truck is more attractive for small quantities of CO_2. However the social acceptance of CO_2 pipelines, as well as the potential magnitude of the demand for disposal in a given region have also to be taken into account.

While pipeline transportation is an established technology, CO_2 transportation by ship is an alternative to offshore pipeline transport, in particular when CO_2 has to be transported over large distances. CO_2 is currently transported by ship but only in very limited quantities, tankers similar to those used to transport liquefied petroleum gas are used. The following figure illustrates the dependency of the transportation costs, including compression, on the transport distance.

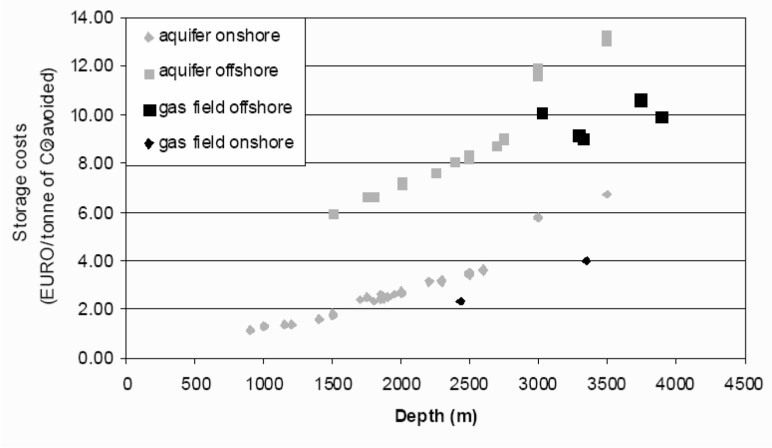
Figure 3-3: Relation between transport distance and costs of compression and transport



Source : (TNONITG & Ecofys, 1999; Ecofys & TNO-NITG, 2002)

Cost estimates of sequestration in disused gas fields range from 1 to 8 €/tCO_2 avoided, depending on the depth of the reservoir, re-use of facilities and on- or offshore location (TNONITG & Ecofys, 1999; Ecofys & TNO-NITG, 2002). Figure 3-4 shows the relation between depth and storage costs for reservoirs that are able to store 1 Mtonne of CO_2 per year for 25 years.

__Figure 3-4: Sequestration costs of CO_2 versus depth for disused gas fields and aquifer traps that are representative for the setting in the Netherlands__



Source : (TNO-NITG & Ecofys, 1999)

Offshore costs are substantially higher because of the requirement of a platform. Costs for storage in empty natural gas fields are somewhat lower than for storage in aquifers because of the lower costs for exploration and for monitoring.

The cost of injecting CO_2

The cost of injecting CO_2 into geological reservoirs for purposes of storage will depend on the type of reservoir and of its physical properties, capacity for storage, amount of work necessary to access the reservoir (e.g. depth and number of wells), CO_2 flow rate, and the value of any saleable products generated as a result (e.g. through enhanced production of hydrocarbons). Monitoring of the stored CO_2 will also be necessary. Because of the number of relevant parameters, there can be a large range of CO_2 injection costs for any given combination of CO_2 sources and storage reservoirs.

The relationship between the cost of storage and the global capacity for storage

Estimates of the global capacity for storage in various geological reservoirs have been gathered for the IEA Greenhouse Gas R&D Programme (Freund, 2001). These data are presented as storage capacity cost-curves. Some results are illustrated in Figure 3-5 for depleted oil fields; this includes an allowance for CO_2 transport costs from likely sources. The effect of enhanced oil recovery can be seen in the negative intercept which results from the income generated due to the extra oil produced as a result of CO_2 injection into these fields. Figure 3-6 shows a similar curve for depleted gas fields – unlike the oil fields case, there is no compensating enhancement of production. Figure 3-7 shows a similar curve for storage of CO_2 in unmined coal deposits, where again there may be opportunities for enhanced recovery of coal bed methane as a result of CO_2 injection.

__Figure 3-5: Cost of storage in depleted oil fields (Source: Freund, Davison 2002)__

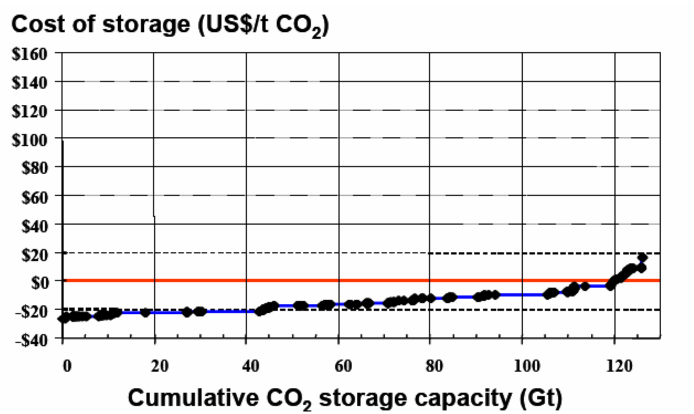


Figure 3-6: Cost of storage in depleted gas fields (Source : Freund, Davison 2002)

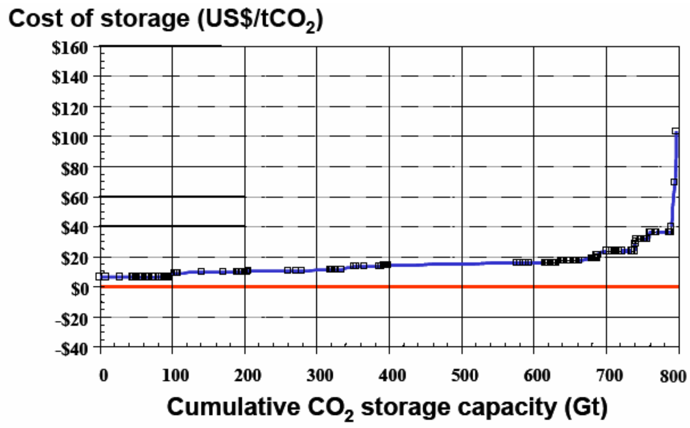
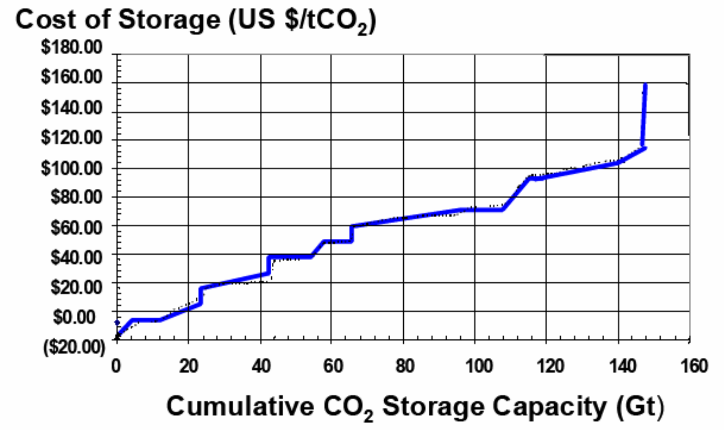


Figure 3-7: Cost of storage in unmined coal deposits (Source : Freund, Davison 2002



According to IAE (2004, p 17), current estimates for large scale capture systems (including CO_2 pressurization, excluding transportation and storage) are 25-50 $/t$CO_2$ but are expected to decrease as the technology is developed and deployed. If future efficiency gains are taken into account, costs could fall to 10-25 $/t CO_2 for coal-fired plants and to 25-30 $/t$CO_2$ for gas-fired plants. However it is very difficult to get agreement on something as critical as the slope of the cost curve.

The work underway to assess CO_2 storage potentials is focused on some of the regions where there are significant emissions of CO_2 from stationary sources, such as North America and Europe. It is also likely that CO_2 capture and storage when implemented as a mitigation option will be applied in these regions at an early stage before any world-wide implementation schedule. However, there are other regions of the world where interest for CCS should be very high, but where up to know only limited research is underway to assess the geological storage capacities. These regions include South East Asia (only Japan is undertaking work in this region) and the Indian sub-continent. Research activities, therefore, need to be developed and initiated also in these areas of the world.

3.2. Presentation of CCS in POLES

3.2.1. Introduction of CCS technologies

In order to simulate the long term dynamics of CO_2 capture and storage within geological reservoirs three power generation and two hydrogen generation technologies have been retained at this stage :

PFC + CCS => PSS Pressurized Supercritical with Sequestration

ICG + CCS => CGS integrated Coal Gasification with Sequestration

GGC + CCS => GGS Gas powered Gas turbine in combined cycle with Sequestration

GSR + CCS=> GSS Gas Steam reforming with Sequestration

CPO + CCS=> CPS Coal Partial oxidation with Sequestration

The simulation of carbon capture and sequestration encompasses the following steps:

- Calculation of the capture and storage costs
- Calculation of the carbon stored for each country and at world level
- Calculation of the unit cost of the carbon stored

3.2.2. Capture and storage cost

The competition between the technologies with and without CO_2 capture and storage needs taking into account of the corresponding costs. The cost of capture tends to be the dominant item for current technology. The corresponding hypothesis concerning the components of the capture costs are presented in the following table:

Table 3-1: Hypothesis for the capture costs

Capture Cost		**Pulverised coal (supercr.). - w. C&S**			**IGCC - Coal - w. C&S**			**Gaz turbine - Combined cycle - w. C&S**		
99 €		2000	2025	2050	2000	2025	2050	2000	2025	2050
CO2 Capture Inv	€/kW	953	667	428	508	336	192	395	336	214
FOM cost	€/kW/y	7	6	6	10	9	9	4	4	3
Fuel efficiency ratio	%	80%	83%	85%	84%	89%	89%	87%	93%	93%
VOM cost	€/ MWh	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

Differential Cost		**Gas steam reforming - w. C&S**			**Coal partial oxydation w. C&S**		
99€ - 95$		2000	2025	2050	2000	2025	2050
CO2 Capture Inv	€/M3d	22	16	17	69	65	53
FOM cost	€/M3d/y	0.28	0.26	0.25	0.71	0.67	0.63
CCS rate	%	75%	78%	80%	80%	83%	85%
VOM cost	toe	18	17	16	50	40	30

Source : TechPOLES

As emphasised before, the cost of transmission is a function of the amount of CO_2 being shipped and of the transmission distance. The cost of storage is a function of capacity, which varies from country to country and according to the type of storage reservoir.

Investment costs for the technologies with sequestration are the sum of the investment cost of the technology without sequestration, of the capture and of the storage, all converted in €/kwh in the case of the electricity technologies and in €/m3d for hydrogen production. For example, the investment cost of CPS is calculated according to following:

$$\text{ACINH}_{[\text{ALLC,CPS}]} = \text{ACINH}_{[\text{ALLC,CPO RD}]} + \text{ACIN1}_{[\text{ALLC,CPSC RD}]+} + \text{ACIN1}_{[\text{ALLC,CO2SEQ RD}]}/0.000257/\text{ACEFH}_{[\text{ALLC,CPS}]}*1.09*44/12*(1-\text{KSCOALH}_{[\text{ALLC,CPS}]})/365*\text{ACAFH}_{[\text{ALLC,CPS}]}$$

The investment cost takes into account the two factor learning curves separately for the capture and the sequestration. Generally the investment cost of the technologies with capture and sequestration may be around 75 % more expensive then the corresponding technologies without sequestration. Overall efficiencies are also around 10% lower. Because of more equipments for compression, injection … fixed costs for operation and maintenance are supposed to be 10% higher than in technologies without sequestration, while variable O&M costs are supposed to be 3-4 times higher.

The unit cost of hydrogen production by coal partial oxidation with sequestration is:

$$\text{PRODCOSTH}_{[\text{ALLC,CPS}]} = \text{ACFCH}_{[\text{ALLC,CPS}]+} \text{ACVCH}_{[\text{ALLC,CPS}]} \qquad \text{(in €99/toe)}$$

The variable cost of the technology with sequestration can be impacted by three types of factors:

- The quantity of carbon sequestrated.

- In terms of transport, the increase in quantity may decrease the unit cost, on the other hand given that the capacity for underground storage is limited the variable cost is supposed to increase with total cumulative storage.
- The third factor refers to the technology improvement trend.

$$\mathrm{ACVCH}_{[\mathrm{ALLC,CPO}]}=(\mathrm{ACVOH}_{[\mathrm{ALLC,CPO}]} + \frac{\mathrm{ETCOAL}_{[\mathrm{ALLC,INDUS}]} * (1 - \mathrm{KSCOALH}_{[\mathrm{ALLC,CPS}]} + \mathrm{CPSCOAL}_{[\mathrm{ALLC,INDUS}]}}{\mathrm{ACEFH}_{[\mathrm{ALLC,COAL}]}})$$

$$* (1+ \mathrm{TRSS}_{[\mathrm{ALLC}]}) * \left(\frac{\mathrm{LIMST}_{[\mathrm{ALLC}]}}{\mathrm{LIMST}_{[\mathrm{ALLC}]} - \mathrm{CUMST}_{[\mathrm{ALLC}]}}\right)^{\mathrm{ELST}_{[\mathrm{ALLC}]}} \qquad \text{(in €99/toe)}$$

where:

LIMST[ALLC] is the limit of the capacity of storage,

CUMST[ALLC] is the cumulative storage of carbon,

ELST is the elasticity of storage which take into account the increase of the distance.

TRSS = -0.012 - technological trend of sequestration delivery & storage cost

3.2.3. Carbon stored by sequestration

Total carbon stored by the sequestration is calculated in the following way:

$$\mathrm{CARBONST}_{[\mathrm{ALLC}]} = \left(\frac{\mathrm{EP}_{[\mathrm{ALLC,GGS}]}}{\mathrm{ACEF}_{[\mathrm{ALLC,GGS}]}} * \mathrm{KSGAS}_{[\mathrm{ALLC,GGS}]} + \mathrm{GAFINHYDR}_{[\mathrm{ALLC}]} * \mathrm{KSGASH}_{[\mathrm{ALLC,GSR}]}\right) *$$

$$\mathrm{CARBON\ CONTENT}_{[\mathrm{GAS}]} +$$

$$\left(\frac{\mathrm{EP}_{[\mathrm{ALLC,PSS}]}}{\mathrm{ACEF}_{[\mathrm{ALLC,PSS}]}} * \mathrm{KSCOAL}_{[\mathrm{ALLC,PSS}]} + \left(\frac{\mathrm{EP}_{[\mathrm{ALLC,CGS}]}}{\mathrm{ACEF}_{[\mathrm{ALLC,CGS}]}} * \mathrm{KSCOAL}_{[\mathrm{ALLC,CGS}]} +\right.\right.$$

$$\mathrm{SOFINHYDR}_{[\mathrm{ALLC}]} * \mathrm{KSCOALH}_{[\mathrm{ALLC,CPO}]}) * \mathrm{CARBON\ CONTENT}_{[\mathrm{COAL}]}$$

The carbon stored by sequestration in world level each year (in k*tC) is:

$$\mathrm{CARBONST\ WRD} = \sum_{\mathrm{ALLC}} \mathrm{CARBONST}_{[\mathrm{ALLC}]}$$

3.2.4. Reductions of emissions by sequestration

In order to take into account the sequestration in sectoral emissions, the corresponding emissions are corrected by a sequestration coefficient (KS) that varies according to energy sources and technologies.

As an example carbon emissions from hydrogen sector (in ktC) are:

$$\mathrm{EM\ CARBON\ TOT\ HYDR}_{[\mathrm{ALLC}]} = \sum_{\mathrm{FUEL}} \mathrm{EM\ CARBON\ HYDR}_{[\mathrm{ALLC,FOSSILFUEL}]}$$

Where:

$\mathrm{EM\ CARBON\ HYDR}_{[\mathrm{ALLC,GSS}]} = \mathrm{GAFINHYDR}_{[\mathrm{ALLC,GSS}]} * (1-\mathrm{KSGAS}) * \mathrm{CARBON\ EMF\ HYDR}_{[\mathrm{ALLC,GAS}]}$

$\mathrm{EM\ CARBON\ HYDR}_{[\mathrm{ALLC,CPS}]} = \mathrm{SOFINHYDR}_{[\mathrm{ALLC,CPS}]} * (1-\mathrm{KSCOAL}) * \mathrm{CARBON\ EMF\ HYDR}_{[\mathrm{ALLC,COAL}]}$

where : KSGAS, KSCOAL- sequestration coefficient (87%).

3.2.5. The total and average sequestration cost

In order to calculate the sequestration cost by ton of carbon, first the total sequestration cost (€99) for each technology is calculated as the difference between the unit production cost of the technology with sequestration and the corresponding one without, multiplied by the quantity of hydrogen or electricity produced by the technology with sequestration.

$$\text{SEQCOSTH}_{[\text{ALLC,GSS}]} = (\text{PRODCOSTH}_{[\text{ALLC,GSS}]}\text{-PRODCOSTH}_{[\text{ALLC,GSR}]}) * \text{HYDRP}_{[\text{ALLC,GSS}]}$$

$$\text{SEQCOSTH}_{[\text{ALLC,CPS}]} = (\text{PRODCOSTH}_{[\text{ALLC,CPS}]}\text{-PRODCOSTH}_{[\text{ALLC,CPO}]}) * \text{HYDRP}_{[\text{ALLC,CPS}]}$$

$$\begin{aligned}\text{SEQCOST}_{[\text{ALLC,PSS}]} = {} & (\text{ACIN}_{[\text{ALLC,PSS}]} * \text{ACIP}_{[\text{ALLC,PSS}]} * 1000 + \text{ACVC}_{[\text{ALLC,PSS}]} * \text{EP}_{[\text{ALLC,PSS}]} * 1\,000\,000) - \\ & (\text{ACIN[}_{\text{ALLC,PFC]}} * \text{ACIP}_{[\text{ALLC,PSS}]} * 1000 + \text{ACVC}_{[\text{ALLC,PFC}]} * \text{EP}_{[\text{ALLC,PSS}]} * 1\,000\,000)\end{aligned}$$

$$\begin{aligned}\text{SEQCOST}_{[\text{ALLC,GGS}]} = {} & (\text{ACIN}_{[\text{ALLC,GGS}]} * \text{ACIP}_{[\text{ALLC,GGS}]} * 1000 + \text{ACVC}_{[\text{ALLC,GGS}]} * \text{EP}_{[\text{ALLC,GGS}]} * 1\,000\,000) - \\ & (\text{ACIN}_{[\text{ALLC,GGC}]} * \text{ACIP}_{[\text{ALLC,GGS}]} * 1000 + \text{ACVC}_{[\text{ALLC,GGC}]} * \text{EP}_{[\text{ALLC,GGS}]} * 1\,000\,000)\end{aligned}$$

$$\begin{aligned}\text{SEQCOST}_{[\text{ALLC,CGS}]} = {} & (\text{ACIN}_{[\text{ALLC,CGS}]} * \text{ACIP}_{[\text{ALLC,CGS}]} * 1000 + \text{ACVC}_{[\text{ALLC,CGS}]} * \text{EP}_{[\text{ALLC,CGS}]} * 1\,000\,000) - \\ & (\text{ACIN}_{[\text{ALLC,ICG}]} * \text{ACIP[ALLC,CGS]} * 1000 + \text{ACVC}_{[\text{ALLC,ICG}]} * \text{EP}_{[\text{ALLC,CGS}]} * 1\,000\,000)\end{aligned}$$

Then the unit sequestration cost (in €99/tC) is calculated as following:

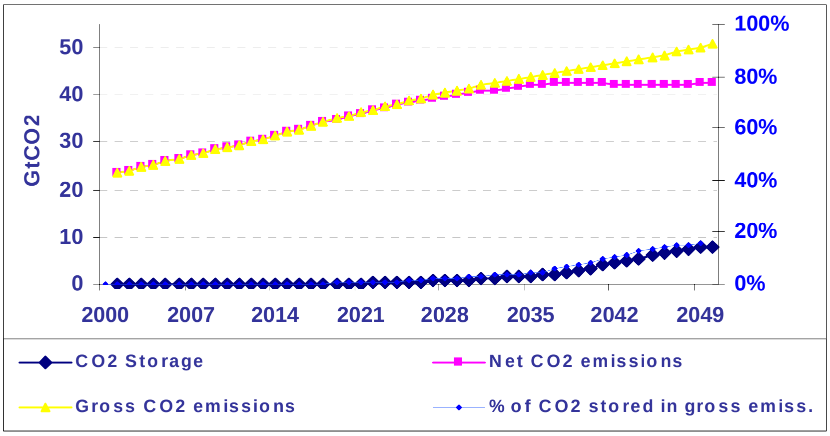
$$\text{SEQCOST WRD} = \text{IF CARBONST WRD} = 0\text{, THEN } 0$$

$$\text{ELSE } \frac{\sum_{ALLC,Techseq} \textbf{SEQCOST[ALLC!,Tech seq]}}{\textbf{CARBONST WRD}*\textbf{1000}}$$

3.3. Results of the model

In the SAPIENTIA REF scenario, CO_2 storage begins after 2030 and attains 8 $GtCO_2$ in 2050 or 16 % of gross CO_2 emissions at that date. This means that in the presence of sufficiently high implicit or explicit taxes on carbon, CCS technologies can indeed be economically attractive on a large scale basis.

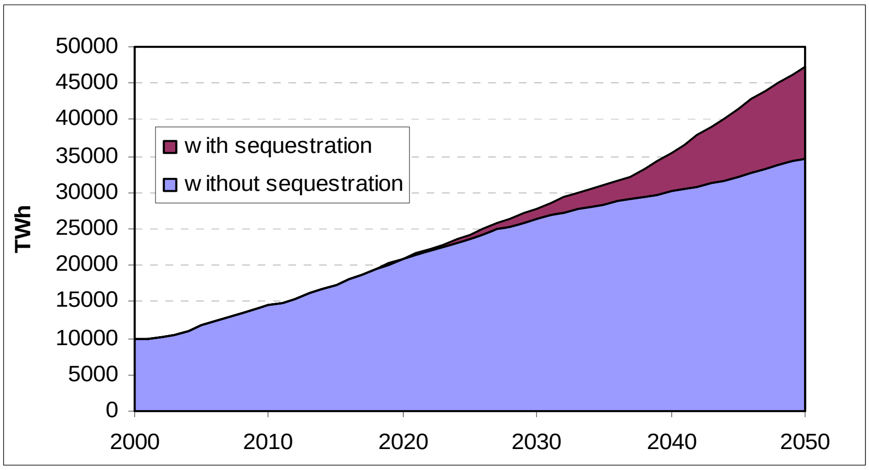
Figure 3-8: CO_2 stored by sequestration, net and gross carbon emissions



Source : POLES model, SAPIENTIA-ref

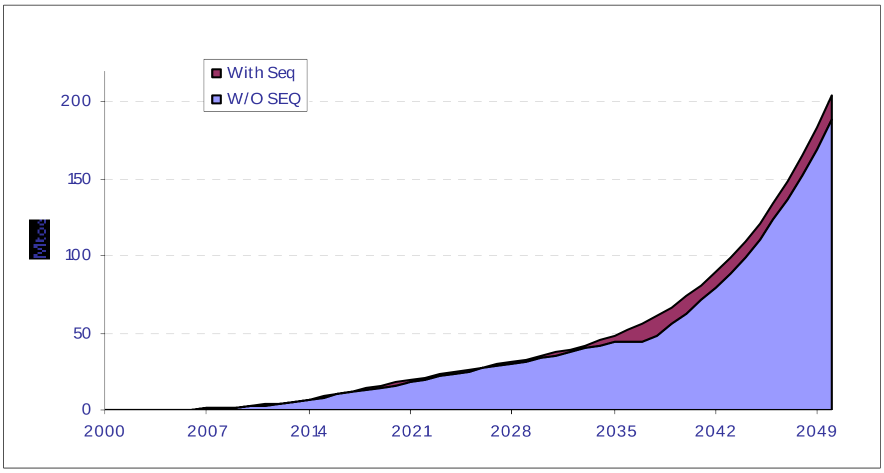
While in hydrogen production the role of the technologies with sequestration is limited to 8%, for electricity production, 27% of the total thermal electricity is generated by technologies with capture and sequestration (Figure 3-9 and Figure 3-10).

Figure 3-9: Thermal electricity production and the role of technologies with sequestration



Source : POLES model, SAPIENTIA-ref

Figure 3-10: Total hydrogen production and the role of technologies with sequestration



Source : POLES model, SAPIENTIA-ref

4. The Integration of the SAPIENTIA Two Factor Learning Curves and Clustering in the POLES Model

Considerable efforts have been recently made to improve the modelling of technology development in energy models. The conventional approach used to rely exclusively on exogenous forecasts based on expert judgement on technology development and economic performance. In SAPIENTIA, this approach is replaced by the SAPIENTIA Two Factor Learning Curves with clustering, as proposed in the project by NTUA (see Part B-3 in the SAPIENTIA Final Report). This allows to endogenise, at least partially, technological change taking, while into account both the "learning by doing" and “learning by searching” effects with the impact of R&D on technology development. This approach yields projections of technology development which are consistent with historic trends (see Figure 4-1). The SAPIENTIA-ref thus contains a coherent set of assumptions with respect to technology development and results in a set of complex and differentiated dynamics.

Figure 4-1: POLES REF to 2050 with endogenous costs and TFLCs for electricity generation technologies

Source :POLES model, SAPIENTIA-ref

Many technologies show a highly non-linear profile in a 50-70 years long-term perspective. Particularly, during the eighties and nineties, the dynamics of the wind onshore are consistent with the “technology shakeout” hypothesis.

In the case of the fuel-cells a significant learning would be necessary to make this technology competitive with corresponding stationary and mobile conventional ones. In current simulations, the learning by doing and by searching effects are not sufficient to reduce the cost at the level that would be necessary to attain competitiveness compared with the conventional vehicles. In spite of the clustering effects, learning rates are generally lower than those observed for renewables in the last 20 years (shakeout).

Many secondary parameters and effects have to be taken into account for a full understanding of the learning rates (e.g. low load factors amplify the capacity increase, low lifetime amplify the necessary cumulative production …). The analytical approach of the learning dynamics must go on … and be also accompanied by in-depth technology case studies

Table 4-1: Progress in the hydrogen production technologies

	2001	2025	2050	2025/001	2050/2025
GSR					
Investment cost (€/m3d)	46	42	41	90%	98%
Efficiency (%)	75%	82%	82%	109%	100%
Installed capacities (Gm3d)	0	3	4		168%
GSS					
Investment cost (€/m3d)	79	67	65	84%	97%
Efficiency (%)	64%	70%	71%	110%	101%
Installed capacities (Gm3d)	0	0	3		
CPO					
Investment cost (€/m3d)	117	96	83	82%	87%
Efficiency (%)	50%	60%	60%	119%	101%
Installed capacities (Gm3d)	0	5	5		110%
CPS					
Investment cost (€/m3d)	202	173	154	86%	89%
Efficiency (%)	35%	42%	44%	121%	104%
Installed capacities (Gm3d)	0	0	2		
BPY					
Investment cost (€/m3d)	124	88	78	71%	89%
Efficiency (%)	65%	65%	65%	100%	100%
Installed capacities (Gm3d)	0	6	91		1417%
SHT					
Investment cost (€/m3d)	463	400	345	86%	86%
Efficiency (%)	100%	100%	100%	100%	100%
Installed capacities (Gm3d)	0	0	0		
NHT					
Investment cost (€/m3d)	972	608	556	63%	92%
Efficiency (%)	45%	50%	58%	110%	117%
Installed capacities (Gm3d)	0	0	0		
WEN					
Investment cost (€/m3d)	461	329	299	71%	91%
Efficiency (%)	31%	36%	37%	115%	103%
Installed capacities (Gm3d)	0	0	7		
WEG					
Investment cost (€/m3d)	131	123	118	94%	96%
Efficiency (%)	75%	75%	75%	100%	100%
Installed capacities (Gm3d)	0	0	0		
WEW					
Investment cost (€/m3d)	358	229	201	64%	87%
Efficiency (%)	100%	100%	100%	100%	100%
Installed capacities (Gm3d)	0	0	0		

REFERENCES

"Capital And Operating Cost of Hydrogen Production from Coal Gasification" Final Report, April 2003, Prepared for The United States Department of Energy National Energy Technology Laboratory (NETL), p. 87.

Alain Feugier « Une réponse à l'effet de serre : la séquestration du CO_2 » LA LETTRE DE LA DIRECTION GENERALE DE L'ENERGIE ET DES MATIERES PREMIERES

Alexis CHATZIMPIROS « A Survey of Energy Technologies for the Long-Term "IEPE, Grenoble September 2001 - Mars 2002, p. 63

Anand B. Rao, Edward S. Rubin, Michael B. Berkenpas „FOR CARBON MANAGEMENT TECHNOLOGIES" Volume 1 – Technical Documentation: Amine-Based CO_2 Capture and Storage Systems for Fossil Fuel Power Plant, Work Performed Under Contract No.: DE-FC26-00NT40935, U.S. Department of Energy National Energy Technology Laboratory, p. 184 http://www.iecm-online.com/documentation/tech_04.pdf

Arthur D. Little "Guidance for transportation technologies: fuel choice for fuel cell vehicles" Final DOE report, February 2002, p. 345.

Bill Leighty "Electrolysis Production of Hydrogen from Wind and Hydropower DOE-NREL, 9-10 Sept 03, Washington, DC

CHALK Steve "Hydrogen, Fuel cells & infrastructure technologies program" Annual program review, May 19th-22nd, 2003, Berkeley, California, p. 60

Chris Hendriks, Wina Graus, Franc van Bergen "Global Carbon dioxide storage potential and costs" ECOFYS by order of the Rijksinstituut voor Volksgezondheid en Milieu, 2002, p. 63.

Committee on Alternatives and strategies for future hydrogen production and use "The hydrogen Economy : opportunities, costs, barriers, and R&D needs" The national academies press February 2004. www.nap.edu, p. 373.

Daniel DELOCHE "Hydrogen fuel for the coming decades" EUROPEAN HYDROGEN ENERGY CONFERENCE, September 2-5 2003

DOE "2003 Merit Review and Peer Evaluation Report" October 2003, p.

F. Di Mario, A. Iacobazzi, R. Infusino, A. Mattucci "Socio-economic Aspects of the Hydrogen Economy Development" ENEA, Hydrogen and Fuel Cells Project, prepared for the Institute for Prospective Technological Studies Joint Research Centre, 2002, p. 37

Jim Dooley, Jae Edmonds, Bob Dahowski, Marshall Wise "Modeling Carbon Capture and Storage Technologies in Energy and Economic Models", IPCC workshop on carbon dioxide capture and storage, Intergovernmental Panel on Climate Change, Expert Meeting on CO_2 Removal and Storage Regina, Canada 19-21 November 2002,p. 161

Joan M. Ogden "HYDROGEN DELIVERY MODEL FOR H_2A ANALYSIS: A SPREADSHEET MODEL FOR HYDROGEN DELIVERY SCENARIOS" Institute of Transportation Studies University of California, Report to the United States Department of Energy Hydrogen, Fuel Cells and Infrastructure Technologies Program For NREL contract number SCM-2-32067-01 UCD-ITS-RR-04-33.pdf, May 15, 2004, p. 12.

John Gale "Overview of Sources, Potential, Transport and Geographical Distribution of Storage Possibilities" IEA Greenhouse R&D Programme IPCC Workshop on Carbon Capture and Storage Regina, Canada, November 18-21, 2002 www.ieagreen.org.uk.

K. R. Schultz, L.C Brown, G. E Besenbruch, C. J. Hamilton „Production of Hydrogen by nuclear energy : the enabling technology for the hydrogen economy" work supported by General Atomics and DOE under Grant N° DE-FG03-99SF21888.

La production Nucléaire de l'Hydrogène, Association Française de l' Hydrogène, Janvier 2001

M.Rostaing: Contrat EURATOM: Production d'hydrogène, CEA Division de Chimie-DGI-GC-G-RT.79/05

Padro Catherine E. Grégoire, Lau Francis "Advances in hydrogen Energy" Kluwer Academic/Plenium Publishers, p.190.

Padro Catherine E. Grégoire, Putsche V. "Survey of the Economics of hydrogen technologies" NREL/TP-570-27079, 1999.

Paul Freund and John Davison "General overview of costs" IEA Greenhouse Gas R&D Programme, Cheltenham, GL52 7RZ, U.K., IPCC workshop on carbon dioxide capture and storage, Intergovernmental Panel on Climate Change, Expert Meeting on CO_2 Removal and Storage Regina, Canada 19-21 November 2002.

Sam Holloway "Storage of fossil fuel-derived carbon dioxide beneath the surface of the earth", Annual Review of Energy and the environment, vol. 26, 2001, p. 145-161.

Soren Anderson and Richard Newell Prospects for Carbon Capture and Storage Technologies January 2003, RFF Discussion Paper 02–68, p. 70

Thermochemical cycles for hydrogen production, IAEA-TECDOC--1085 (Appendix A), International Atomic Energy Agency, Austria

Wade A. Amos "Costs of Storing and Transporting Hydrogen" November 1998, NREL/TP-570-25106, p. 216.

IV. Extensions of the PROMETHEUS Stochastic Model

Nikos Kouvaritakis and Vagelis Panos **ICCS-NTUA**

1. Extensions of the PROMETHEUS Stochastic Model

All models presented so far are essentially deterministic in character. The projections and variants produced using these models provide many interesting insights as to the future course of energy system variables. Such analysis offers a valuable means of exploring possibilities in a transparent and readily justifiable way particularly useful in supporting policy analysis. It does not however give any quantitative indication as to how likely some occurrences may be. Such information is often strategically important and could add a different dimension to the analysis performed. Stochastic models are appropriate tools for providing this type of information however very few of them exist covering energy systems.

ICCS/NTUA has developed PROMETHEUS, a tool capable of performing precisely this type of analysis. Originally conceived as a source of risk information for energy R&D portfolio exploration, PROMETHEUS covers, albeit in a more aggregate way (compared to the deterministic models) all the key aspects of the World energy system together with key global environmental issues (global temperature change). The model recognises three main sources of uncertainty:

- Uncertainty regarding assumptions and the evolution of exogenous variables
- Variation in variables that are not explicitly modelled since they are considered relatively unimportant but could cumulatively cause deviations (such deviations are usually assumed to be zero centred)
- Uncertainties arising from imperfect knowledge of the system and notably the parameters included in the model.

PROMETHEUS is a self-contained energy model consisting of a set of stochastic equations and identities (in total over 2100 equations). All exogenous variables, parameters and error terms in the model are stochastic and there is explicit representation of their distribution including terms of co-variance. As a result all endogenous variables are also stochastic. It also contains stochastic relations describing technology improvement dynamics (both learning by research and experience). The output from PROMETHEUS consists of a massive Monte-Carlo set representing at least 1000 alternative scenarios.

PROMETHEUS provides the probabilistic input necessary for giving the ISPA tool (the R&D policy exploration facility) its ‘hedging’ characteristics. Work on PROMETHEUS attempts to answer primarily two basic questions:

- How large are the uncertainties associated with the impacts of specific R&D actions on the different policy objectives
- How do these uncertainties impact on each other (i.e. does an overestimate of the possible impact of an R&D action on a target indicator imply an overestimate of the impact of another measure on the same or another indicator? Or on the contrary does it imply an underestimate?)

These are fundamental questions for policy exploration, especially in a field like R&D budgeting where uncertainties on the efficacy of actions can be very considerable due to the very nature of R&D which is effectively a speculative activity.

Work in SAPIENTIA has concentrated on the re-estimation and very substantial expansion of the PROMETHEUS stochastic model as developed in SAPIENT (which had limited the scope to power generating technologies). The ultimate aim has been to measure uncertainties arising from a great variety of sources: uncertainties on the various assumptions, errors on parameter estimates, errors arising from omitted factors.

A fundamental task undertaken within SAPIENTIA has been the extension of the model's forecast horizon to the longer term (2050). To this end, work on PROMETHEUS has followed closely the specification of the longer term in POLES albeit in a less detailed fashion, especially with regard to regional and sectoral disaggregation. The extension to the 2050 time horizon has entailed significant changes in the PROMETHEUS modeling system with regard to the identification and introduction of new technologies and the modification of the structure of the model. Accordingly, PROMETHEUS has been extended to cover a more detailed transportation sector and to incorporate a Hydrogen Production, Storage and Delivery sub-model. In all, 22 additional technologies are represented in the new version (4 large scale power generation, 4 very low emission vehicles, one distributed power generation and 9 Hydrogen Production technologies).

The Hydrogen sub-module considers 9 technologies to compete on the supply side for the centralised production of H_2. On the demand side, hydrogen is introduced in the competitive market of distributed electricity production (through stationary fuel cells) and in the road transport sector (through fuel cell cars and the hydrogen internal combustion engine car).

The hydrogen and electricity systems are connected on the supply side through the electricity price in grid electrolysis and on the demand side through the competition between the decentralised fuel cell electricity production and the electricity from grid.

PROMETHEUS also incorporates competition between gaseous or liquid storage options and between pipelines and trucks for hydrogen delivery options.

Other important developments on the PROMETHEUS model include the endogenisation of climate policy (where climate change -as it is perceived to occur- affects the climate policy intensity) and the endogenisation of R&D, by making it dependent on energy costs, while renewable and CO_2 capture technologies shares in total R&D are affected by energy costs and the carbon value (climate policy intensity).

Finally, PROMETHEUS has been extended to incorporate technology dynamics for 51 technological options for electricity production, hydrogen production and passenger cars. These include:

- Capital costs parameters for 44 technological options
- Fixed O&M costs for 34 technologies; although they are basically labour costs, technical progress has been assumed based on the increased automation, reliability and the economies of scale
- Variable cost parameters for 7 technologies, adjusted for efficiency.
- Efficiency parameters for 20 technologies

D. Projections and Scenarios

I. Baseline Scenario

Nikos Kouvaritakis and Vagelis Panos (PROMETHEUS)	**ICCS-NTUA**
Patrick Criqui and Silvana Mima (POLES)	**LEPII-EPE**
Hal Turton (ERIS)	**IIASA**
Leonardo Barreto and Socrates Kypreos (GMM)	**PSI**
K. Smekens (MARKAL)	**ECN**

1. Common Assumptions

1.1. Key Assumptions

The SAPIENTIA Reference projection provides a detailed description of the world energy system to 2050. While most developments in the energy system – including the technology cost and performance dynamics – are endogenous to the model, three sets of exogenous hypotheses have to be defined before any simulation of the model: the population and economic growth by region / country, the world oil and gas resources by key producing area and finally the GHG abatement policies adopted in each region.

Altogether, these sets of hypotheses form the key drivers – population, economic growth – and constraints – "upstream" with oil and gas resources, "downstream" with emission limitations – that command the development and structural transformations of the system in the very long-term. They are presented below, before the description of the development of the world energy system in the next section.

1.1.1. Population and economic growth by main world region

World population trends

World population is expected to increase from little more than 6 billions today to 8.9 billions in 2050 with a marked decrease in average growth, which is due to the demographic transition and anticipates the stabilization in total population in the second half of the century. By 2030 four countries or regions – India, China, Africa and Asia South & South-East (or Rest of Asia) – will represent the same level of population, i.e. 1.4 billion. In 2050 and on the basis of on-going trends Africa may be the most populated world region with 1.8 billion, followed by the Rest of Asia, India and China (Table 1-1).

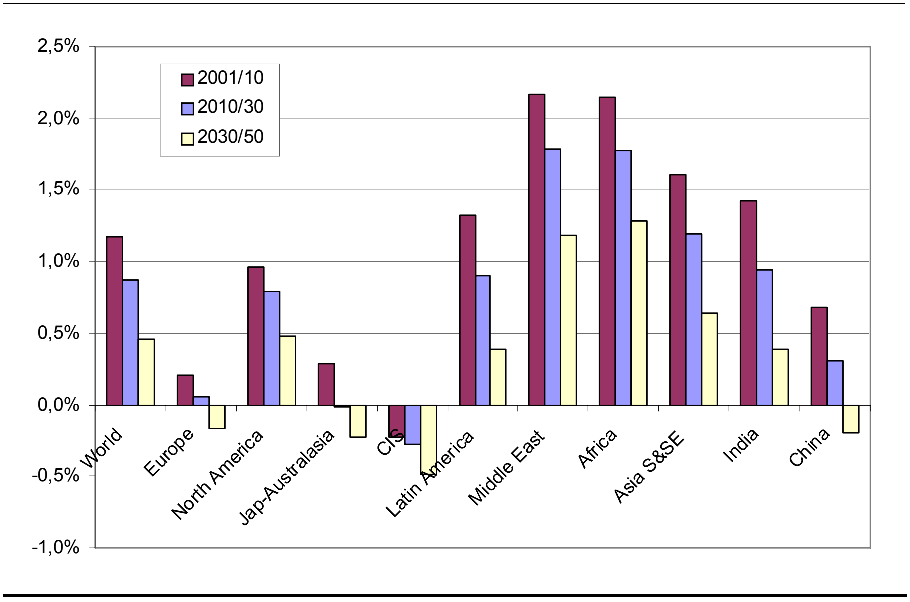
Table 1-1: World population projection (millions)

						Annual % change		
	2001	**2010**	**2020**	**2030**	**2050**	*2001/10*	*2010/30*	*2030/50*
World	**6113**	**6792**	**7496**	**8082**	**8864**	**1,2%**	**0,9%**	**0,5%**
Europe	588	599	605	606	586	0,2%	0,1%	-0,2%
North America	316	345	376	404	444	1,0%	0,8%	0,5%
Jap-Australasia	157	161	162	161	154	0,3%	0,0%	-0,2%
CIS	281	276	270	261	237	-0,2%	-0,3%	-0,5%
Latin America	520	585	649	700	756	1,3%	0,9%	0,4%
Middle East	169	205	249	292	369	2,2%	1,8%	1,2%
Africa	814	986	1189	1401	1808	2,1%	1,8%	1,3%
Asia S&SE	963	1111	1269	1407	1600	1,6%	1,2%	0,6%
India	1032	1173	1311	1415	1530	1,4%	0,9%	0,4%
China	1272	1351	1415	1436	1381	0,7%	0,3%	-0,2%

Source: POLES model hypotheses, adapted from UN population projections

Due to the ageing phenomenon, the population is expected to decrease in four world regions by the end of the projection period, at an average rate of -0.2 %/yr for Europe, Japan-Australasia and China, and of -0.5/yr for the Community of the Independent States. The Middle-East and Africa show the highest growth rates over the period, with still a more than one percent increase between 2030 and 2050 (following figure).

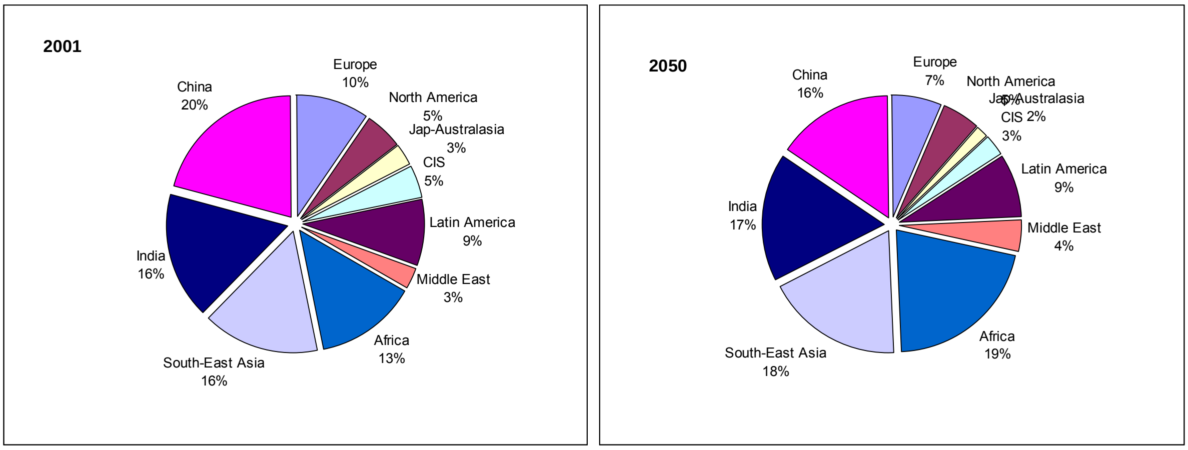
Figure 1-1: Yearly average change in population, world and key regions (%/yr)



Source: POLES model hypotheses, adapted from UN population projections

Surprisingly enough, in spite of these differentiated dynamics, the structure of world population doesn't show dramatic changes. However, the share of the currently industrialised – or Annex 1 – countries decreases from 23 to 18 % of total between now and 2050. Among the non-Annex 1 regions the most noticeable changes are the decrease in China's share of world population, from 20 to 16 %, and the rise of Africa, from 13 to 19 % (see following figure).

Figure 1-2: World population structure, 2001 and 2050



Source: POLES model hypotheses, adapted from UN population projections

Per capita GDP growth

Along with population growth, per capita GDP growth is the second key driver to economic growth. In this economic projection, world average per capita GDP growth is supposed to decrease, from 2.7 %/yr until 2010, to 2.2 %/yr in the 2010-2030 period, and 1.7 %/yr in the 2030-2050 period (Table 1-2). To a large extent, the per capita GDP growth corresponds to the increase in global productivity of labor, however it is also strongly influenced by the age structure of the population, the occupation rates and workforce mobilization ratios.

Table 1-2: Per capita GDP growth, world and key regions (€99/cap, PPP)

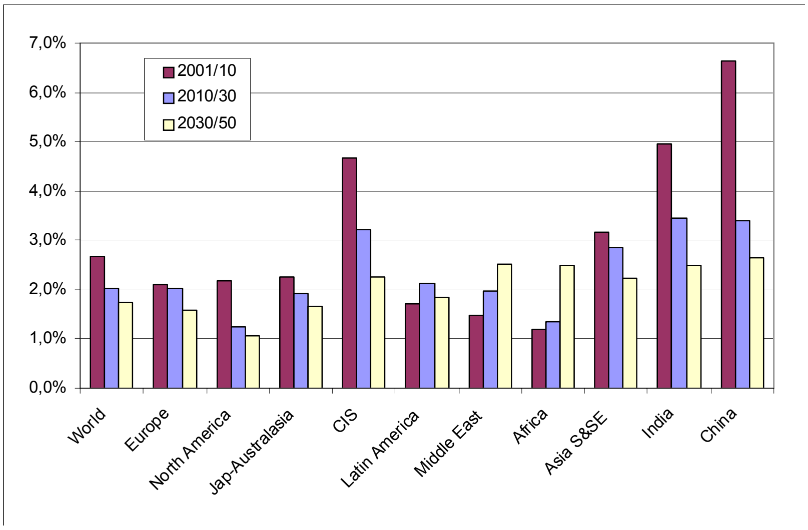
						Annual % change		
	2001	**2010**	**2020**	**2030**	**2050**	*2001/10*	*2010/30*	*2030/50*
World	**6907**	**8764**	**10880**	**13107**	**18513**	**2,7%**	**2,0%**	**1,7%**
Europe	17533	21124	26260	31496	43005	2,1%	2,0%	1,6%
North America	31614	38341	43693	49146	60584	2,2%	1,2%	1,1%
Jap-Australasia	22775	27864	33713	40770	56786	2,3%	1,9%	1,7%
CIS	5204	7852	11263	14797	23174	4,7%	3,2%	2,3%
Latin America	6557	7645	9569	11636	16754	1,7%	2,1%	1,8%
Middle East	5794	6606	7945	9741	16007	1,5%	2,0%	2,5%
Africa	2044	2277	2612	2983	4866	1,2%	1,4%	2,5%
Asia S&SE	3367	4458	6044	7803	12146	3,2%	2,8%	2,2%
India	2676	4133	6087	8148	13313	4,9%	3,5%	2,5%
China	3778	6740	9728	13171	22173	6,6%	3,4%	2,6%

Source: POLES model hypotheses, adapted from CEPII 2030 projections

Per capita GDP growth is strongly differentiated across regions, with three typical profiles:

- Europe, North America and Japan-Australasia sharing similar profiles of slow decrease from current 2 %/yr growth rate to 1-1.5 %/yr between 2030 and 2050
- The three Asian regions, and also the CIS show a more rapid decline, but from current extremely high levels, towards growth rates in the range of 2-2.5 %/yr in the 2030-2050 period.
- Finally Latin America, but more markedly the Middle-East and Africa benefit from increases in per capita GDP growth, from current low levels, again to 2-2.5 %/yr in the 2030-2050 period.

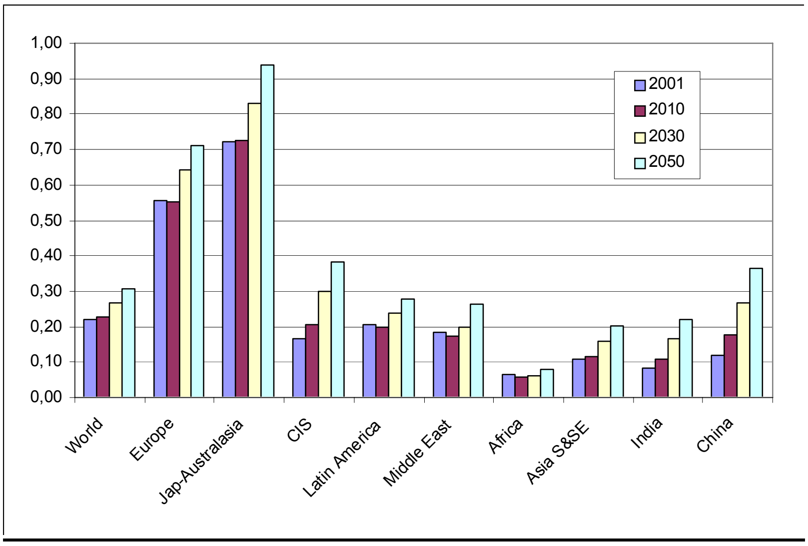
Figure 1-3: Per Capita GDP growth rates, world and key regions (%/yr)



Source: POLES model hypotheses, adapted from CEPII 2030 projections

As a result of these differentiated trends, the projection describes a certain degree of convergence in regional per capita GDP. In four of the seven non-OECD regions, today's average per capita GDP represents 10 % or less of the same indicator in the region with the highest level – North America –while in the other three it represents about 20 %. According to this projection, the situation will be significantly altered in 2050, with all non-OECD regions except Africa showing a per capita GDP level of more than 20 % that of North America, and four of them, including China, reaching the 30 % range (Figure 1-4). A certain degree of convergence also takes place among OECD countries, as the per capita GDP relative to North America index also increases in Europe, from 55 % today to 70 % in 2050, and in Japan and Australasia, from 70 % to 95 %. This is consistent with the fact that North America is the richest and more mature economy, thus the one that may encounter in the first place the limitations in per capita GDP and productivity increase.

Figure 1-4: Per Capita GDP relative to North America's level



Source: POLES model hypotheses, adapted from CEPII 2030 projections

GDP projection, world and key regions

World GDP growth is the result of population and per capita GDP growth and when combining the trends described in the above sub-sections one obtain the resulting image of the world GDP by region. World total output is expected to grow steadily until 2050, although at a pace that progressively slows down, from 3.9 %/yr in the current decade, to 2.9 %/yr in the 2010-2030 period and 2.2 %/yr in the 2030-2050 period. In spite of this slowdown, world output in 2050 is four times that of today (Table 1-3).

Table 1-3: GDP growth, world and key regions (billion €99, PPP)

						Annual % change		
	2001	**2010**	**2020**	**2030**	**2050**	*2001/10*	*2010/30*	*2030/50*
World	**42224**	**59524**	**81559**	**105930**	**164090**	***3,9%***	***2,9%***	***2,2%***
Europe	10312	12660	15900	19079	25194	*2,3%*	*2,1%*	*1,4%*
North America	10003	13225	16432	19843	26887	*3,2%*	*2,0%*	*1,5%*
Jap-Australasia	3583	4497	5474	6558	8731	*2,6%*	*1,9%*	*1,4%*
CIS	1463	2164	3041	3860	5488	*4,4%*	*2,9%*	*1,8%*
Latin America	3410	4474	6210	8145	12658	*3,1%*	*3,0%*	*2,2%*
Middle East	978	1353	1981	2842	5908	*3,7%*	*3,8%*	*3,7%*
Africa	1664	2244	3106	4177	8795	*3,4%*	*3,2%*	*3,8%*
Asia S&SE	3242	4952	7669	10981	19435	*4,8%*	*4,1%*	*2,9%*
India	2763	4847	7980	11531	20367	*6,4%*	*4,4%*	*2,9%*
China	4805	9107	13766	18914	30626	*7,4%*	*3,7%*	*2,4%*

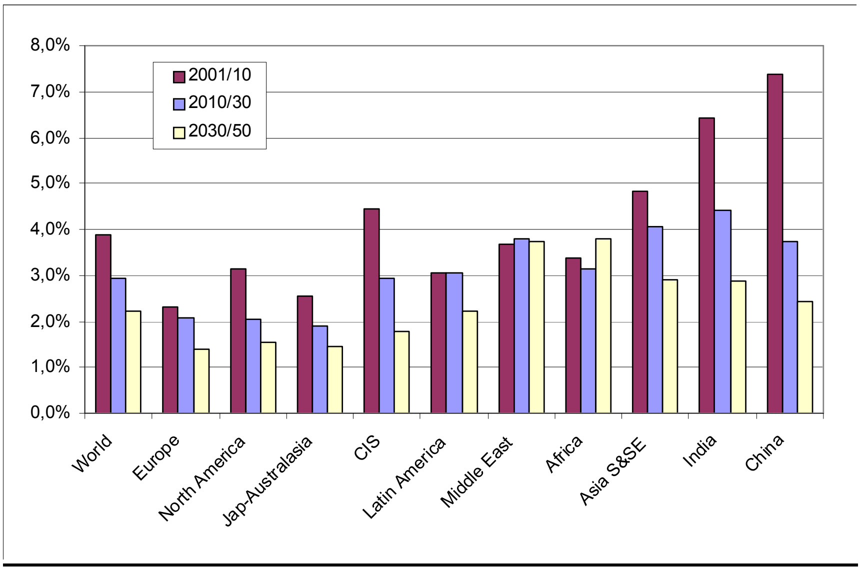
Source: POLES model hypotheses, adapted from CEPII 2030 projections

(i) The Annex 1 regions

In the on-going decade, North America maintains its growth advantage of 0.5 to 1 point of growth on Europe and Japan-Australasia, due to the combined effect of a relatively high growth, both in population and in per capita GDP. This advantage disappears after 2010 and the growth level of the OECD regions converge towards 2 %/yr in the 2010-2030 period and 1.5 %/yr in the 2030-2050 period.

The growth profile is different in the CIS as growth is initially high, due to the recuperation of the transition crisis of the eighties. Growths then slows down to 2.9 %/yr between 2010 and 2030 and then to 1.8 %/yr.

Figure 1-5: GDP growth, world and key regions (%/yr)



Source: POLES model

(ii) Asian growth

In the Asia region, current economic growth rates are extremely high, in particular in India and China, with respectively more than 6 and 7 %/yr. The projection indicates a slowdown in Asian growth after 2010 to about 4 %/yr between 2010 and 2030 in the three regions and then to 2.9 %/yr for India and the Asia South & South-East, and 2.4 %/yr for China.

(iii) The rest of non-Annex 1 regions

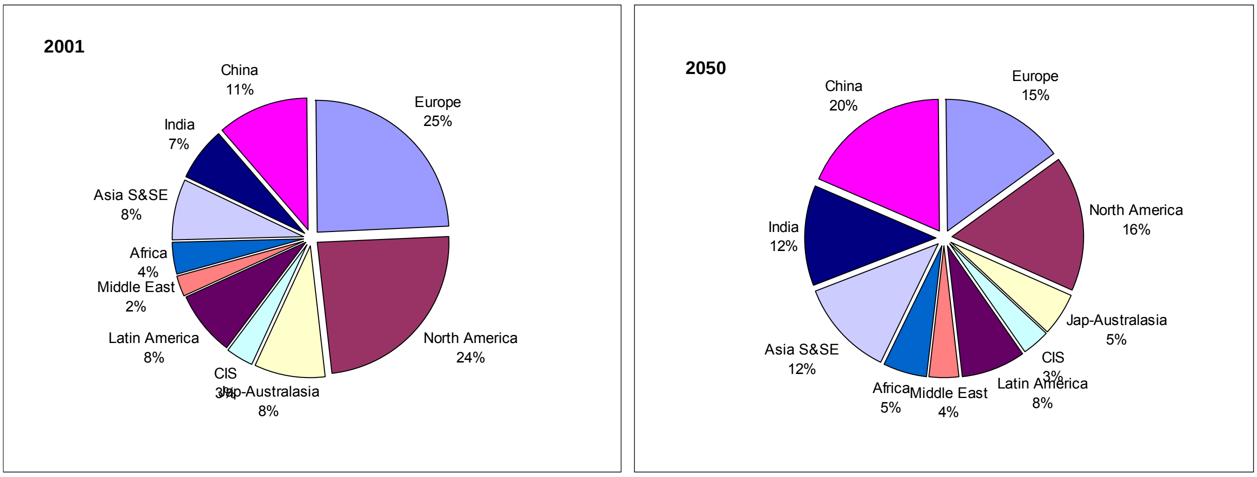
Economic growth profiles are more even in time in the rest of the non-Annex 1 regions: growth is relatively slow in Latin America all over the period, to 3 %/yr until 2030, 2.2 %/yr later equalling the world average during the 2030-2050 period. Africa and the Middle-East show better than average performances after 2010. After 2030 these two regions even show higher economic growth than Asian regions, at 3.8 %/yr. For the Middle-East, this is consistent with the expected increase in the oil and gas price, while for Africa these high growth rate may correspond to the start of a rapid catching-up process, while in terms of per capita GDP Africa is still far beyond all other world regions.

(iv) The regional structure of world GDP

Conversely to what has been noted concerning the world population structure, the outcome of the combined drivers to economic growth correspond to a series of major changes:

- Europe and North America today represent 49 % of world GDP, according to the projection this share will be down to 31 % in 2050.
- Accordingly all Annex 1 countries today represent 60 %, but only 39 % of world output in 2050.
- Most of the gains in world output's share benefit to Asia that in 2050 will represent 44 % of total, against 26 % today.
- The gains of the rest of non-Annex 1 countries are more limited as their share in world output increases only from 14 % today to 17 % in 2050.

Figure 1-6: World GDP structure, 2001 and 2050



Source: POLES model

The picture that results from the 2050 projection used in the SAPIENTIA study is one of a significant increase in the size of the world economy (multiplication by four) in spite of the slowdown in economic growth that is expected by the end of the projection. The picture is indeed dominated by the full emergence of Asia, the economy of which is expected to be multiplied by seven between today and 2050, also in spite of a marked slowdown after 2010. By the end of the projection, Europe, North America, China and India may constitute players of comparable size in the world economy that altogether represent two thirds of world product (Figure 1-6).

1.2. Climate Policy Assumptions

In the course of the specification of the SAPIENTIA Baseline scenario, the need for an alternative reference case which would include some climate policy response was identified. This requirement arose primarily from reflection on the status of the baseline of PROMETHEUS: assuming no policy response in the Baseline would be equivalent to stating that there is no probability of such policy anywhere in the World for the next 50 years. Clearly such an assumption would alter drastically the nature of PROMETHEUS Baseline results from “maximum likelihood” to conditional distributions. PROMETHEUS provides the distribution characteristics (mainly the variances and co-variances) of the impacts of specific R&D actions to be used as input for the integrated R&D policy analysis using the ISPA tool. Results from large deterministic models are used to provide the mean impacts in these integrated exploration exercises. Since mean impacts almost certainly depend on the presence of climate policies (encouraging some technological options while discouraging others) and in order to retain consistency within the integrated policy assessment process it was deemed necessary to perform the R&D sensitivity exercises within the context of some “median” climate policy stance.

Since no truly scientific expertise regarding the timing, extent, nature and probability of such policies is really available, it was decided to resort to a Delphi type methodology among partners in order to derive the essential input for this “with policy” scenario. Key assumptions underlying the scenario are:

- The EU leads and will continue leading the World climate change abatement effort.
- Less developed economies will not undertake abatement policies unless industrialised countries are also committed and at any rate their effort as measured by marginal abatement costs will be smaller or equal to those pertaining to the latter.
- The measure of climate policy effort will be an implicit carbon value rather than GHG emission constraint, which would render model implementation much more complex and the policy definition highly dependent on the Baseline and its attributes.
- There is no feedback from the climate change process (or emission levels) to the severity of the policy. This assumption is unrealistic in the sense that such policies would normally respond to the climate change problem and would become more urgent if the situation deteriorates (rapid growth of emissions). On the other hand it could be argued that a more severe problem would also make the cost of dealing with it higher and increase the reluctance to tackle it. At any rate the main reason for avoiding an endogenous policy has been the implied complexity of the questionnaire and the risk of obtaining through it biased and inconsistent results.
- Non-energy related GHGs are assumed included in the abatement effort. On the other hand for the purposes of PROMETHEUS a probability that they are left out due to monitoring difficulties is considered and partners were requested to provide input concerning this probability.

In this context, ICCS-NTUA undertook the circulation of a questionnaire among SAPIENTIA partners, requesting their expertise with regard to global climate policy scenarios and their realisation likelihood in the future. For the purposes of the questionnaire, the world was divided into three geopolitical regions: EU, Rest of OECD (‘Old’ Industrialised members) and Rest of the World. The questionnaire was designed to contain three sections, each referring to one of these regions, while each section comprised of a series of questions on the realisation probabilities and effort intensity of alternative future scenarios. The questions were designed to elicit and develop expert judgement on climate policy issues with regard to a horizon extending to 2100, divided into 6 sub-periods; for the period to 2050 input was requested on a decade-to-decade basis, whereas a single projection was requested for the second half of the century.

More specifically for every time segment of the outlook period, partners were requested to furnish their responses using their judgement on the following:

- The probability that the world will undertake no emission abatement effort.
- The probabilities that only the EU will undertake climate change abatement effort and, on that basis, the mean effort intensity measured in terms of mean implicit carbon value.
- The probabilities that the Rest of OECD will undertake an effort equivalent or inferior to the EU and the mean fraction of the EU effective carbon value applicable within the region.

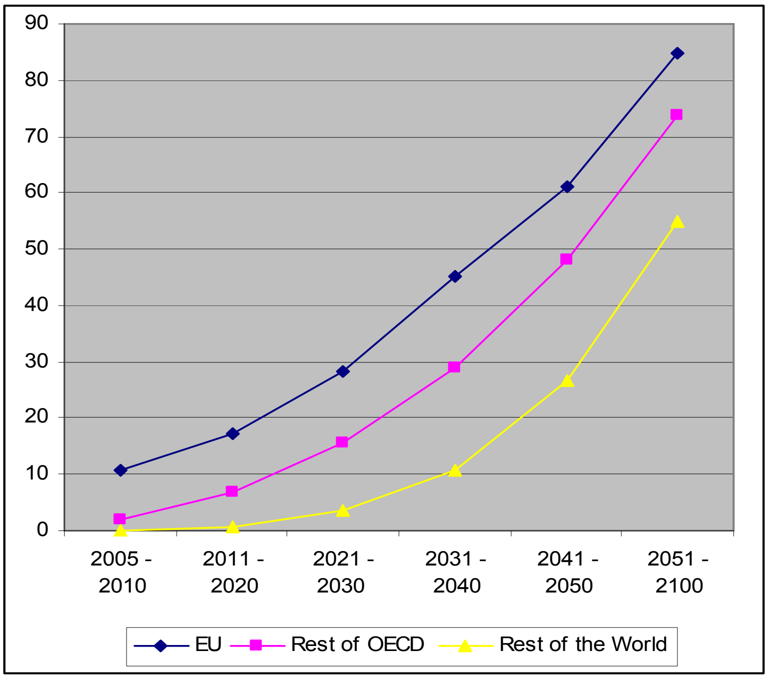
- The probabilities that the Rest of the World will undertake an effort equivalent or inferior to the Rest of OECD and the mean fraction of the Rest of OECD effective carbon value applicable within the region.

1.2.1. Synthesis of Responses

This section presents some key aggregate results as derived from the synthesis of the questionnaire responses. This synthesis provides some insight to the future allocation of climate effort across the three world regions, as perceived by experts participating in SAPIENTIA. In particular, this section documents the assumed evolution of the mean effective carbon values over the outlook as well as the 'mean' probabilities that experts attribute to alternative climate policy outcomes.

The following figure presents the results on the projected mean effective carbon value applicable within the EU, Rest of OECD and Rest of the World regions over time.

Figure 1-7: Mean Effective Carbon Values in Euro99 per tonne CO_2



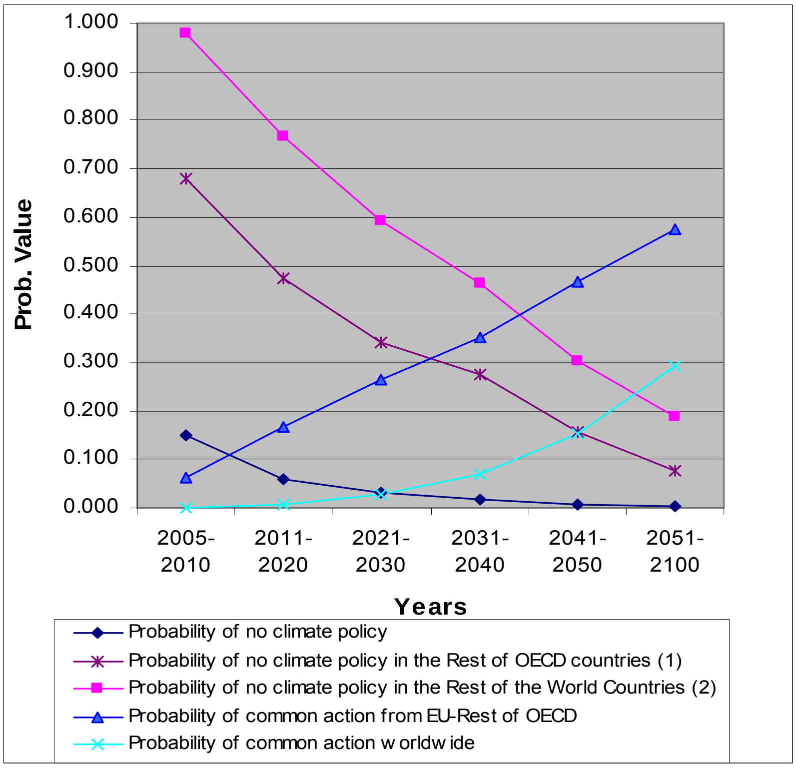
A cursory look at the figure indicates that the environmental threat appears to be perceived over time with different degrees of concern by the different world regions illustrated in their will to adopt varying carbon value levels over time. In all, the figure indicates constantly increasing intensiveness of the climate mitigation policy effort over time. To begin with, the EU is projected to demonstrate the earliest concern on the climate change issue, illustrated in a mean carbon value of 11€ (99) per tonne CO_2 already by 2010. This early commitment from the EU region to tackle climate change can be partly attributed to the regions' current engagement to restrict CO_2 emissions in compliance with the requirements of the Kyoto Protocol. Turning to the post-Kyoto period, the EU mean carbon value increases persistently, sees a fourfold increase to 2040 and reaches a level of 85€ (99) by the end of the century.

With respect to the Rest of OECD region, the results indicate a mean effective carbon value equal to 2€ (99) in the period to 2010, a value significantly lower than the respective estimate for the EU, indicating the US reluctance to engage in restrictive climate policy in the near future. However, the situation in the Rest of OECD region is projected to gradually but strongly reverse in the subsequent periods, illustrated in the continuously increasing mean effective carbon value estimates corresponding to this region for the remainder of the century; this persistent ongoing effort to reduce carbon intensity throughout the century translates into carbon values which range from 2€ (99) at 2010, to 48€ (99) by mid-century and 74€ (99) to 2100. This is further illustrated in the constant increase in the fraction of the Rest of OECD abatement effort relative to the respective EU effort: the ratio of the Rest of OECD carbon value to the respective EU value sees a significant increase from less than one fifth by 2010 to almost four fifths by 2050.

Compared with the industrialised world, the Rest of the World countries display the lowest carbon value levels over time, demonstrating the weakest involvement in promoting an internationally coordinated climate abatement effort throughout the century. More specifically, for the period to 2020, these countries are projected to undertake no or minimal effort illustrated in near zero carbon value estimates. The Rest of the World region is projected to engage in climate action only after the first quarter of the century. It is worth noting here that in terms of the estimated effective carbon value levels this region is projected to reach the present policy intensity of the Rest of OECD only after 2021 and to engage in an effort equal to the initial EU effort only after 2031. The final, end of the century projection projects a carbon value equal to 55€ (99) which indicates that in the longer term third world countries will also engage in stringent climate policy.

Figure 1-8 below illustrates the outcome of the Delphi procedure in terms of the evolution of 'mean' probabilities that experts attribute to some alternative climate policy outcomes over time. Starting from the most 'pessimistic' case which assumes no climate action across the world throughout the century, responses suggest an ever-decreasing probability of such an outcome, even though it features with a non-negligible value at least until 2030. Indeed likelihood of such an outcome is 15% for the period to 2010, registers a sharp decline in the next decade to only 5.9% which is followed by a persistently diminishing trend for the remainder of the century translating to a near-zero probability for the years beyond 2041. In all, the partner's responses suggest an increasing need for concrete decisions on the implementation of a global climate policy in the near future; a need which apparently turns to necessity in the longer-term future when a global dimension of environmental action is advocated.

Figure 1-8: Probabilities of alternative scenarios



---

(1) Even though the EU pursues a policy.
(2) Even though the Industrialised World pursues a policy.

Indeed, the overall picture arising from the figure suggests a gradual formation of an international climate change policy which becomes particularly pronounced mainly after the third decade of the century. This pattern can be strongly attributed to the growing participation from the Rest of OECD and Rest of the World regions to the climate abatement effort, led by the EU. The projected intense EU environmental activity is reflected in high probabilities of climate action, which range from 77% in 2010 to above 85% for the remainder of the century. On the other hand, the Rest of OECD and Rest of the World regions are projected to exhibit limited or no concern on climate change issues at least in the 2010 horizon. With regard to the former region, the survey suggests 70% probability of taking no climate action by 2010 even if the EU pursues one; this picture however is gradually but strongly reversed already from the subsequent decade, by the end of which the region displays 50% probability of engagement in such an action. By the end of the century the chance that the Rest of OECD will not participate in the EU climate change abatement effort is minimal, even if this implies large abatement costs, i.e. high effective carbon values. In a similar context, the projected probability that the Rest of the World countries engage in climate policy is nearly zero for the period to 2010; however on the assumption of increasing concerns on global climate change and facing a gradual synchronisation of effort on behalf of the EU and Rest of OECD regions, the Rest of the World region is also projected to demonstrate increasing willingness to contribute to the development of a global environmental policy in the longer term.

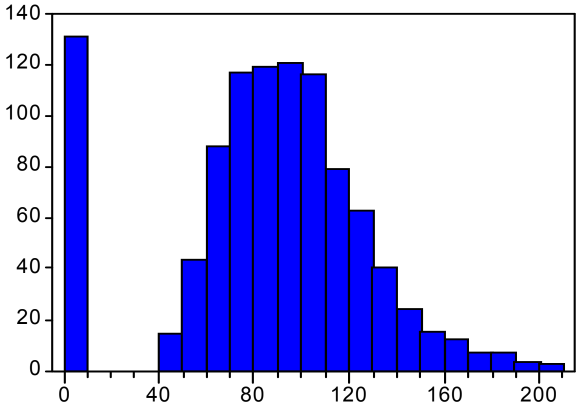
In the short term, the striking feature of the figure above is the persistent reluctance of the Rest of the World region to take any environmental action, coupled with a low degree of coordination of climate activity from the industrialised countries (EU and Rest of OECD regions), a pattern particularly evident until 2020. Nevertheless, the probabilities that the industrialised world will create a permit market and that the Rest of the World will engage in an abatement effort, display converging paths over time, which are projected to intersect just after 2030 at a probability level of about 40%. This point is likely to signal the beginning of a more co-ordinated effort throughout the industrialised and the less developed world, illustrated in a constantly increasing probability of adapting a carbon mitigation strategy for the former and a sharply decreasing likelihood to refrain from such an action for the latter (a pattern which is also depicted in the projected sharp concurrent increase in the likelihood of a world wide permit market which is discussed below).

A combination of these two patterns is embodied in the final ‘common action’ trajectory, which refers to the probability, given by experts, that a permit market will be established across the world or, equivalently, the probability that all three regions will undertake climate abatement effort of equal intensity throughout the period considered. With regard to the 2020 horizon the survey results suggest that the emergence of such a worldwide market is nearly infeasible. In the subsequent decade however and for the remainder of the century experts attribute a slowly increasing probability to the occurrence of such an outcome, a pattern which on the one hand reflects the growing likelihood in the creation of a permit market across the EU and Rest of OECD regions, and the growing contribution to climate abatement policies from the Rest of the World countries on the other. Still, the probability levels remain more or less confined to low values throughout the century (they are projected to reach a peak of about 29% at the second half of the century), illustrating that the global confinement to equal levels of environmental effort is a rather unlikely event, even in the very-long term.

1.2.2. Stochastic Analysis of the Responses

To enable further statistical analysis of the responses, the Monte Carlo simulation technique was employed to the questionnaire responses. In the course of the Monte Carlo experiments, the outcome of the Delphi process was run a thousand times and probability distributions were derived for the carbon values in all regions. Figure 1-9 Figure 1-11 below give the resulting effective carbon value distributions for the EU, the Rest of OECD and Rest of the World regions for the period 2040 to 2050, while Table 1-4 summarises some key results on the carbon values obtained from the Monte Carlo Analysis.

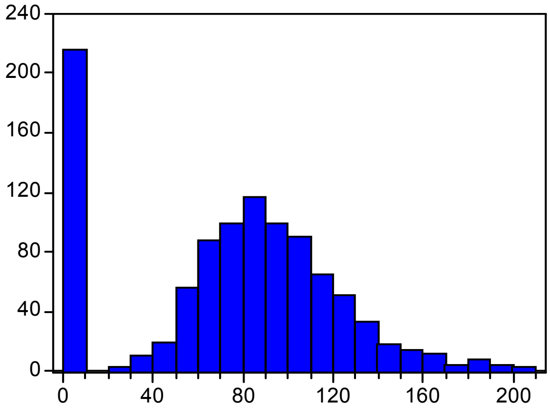
Figure 1-9: Distribution of Effective Carbon Tax 2040-2050 for the EU



Series: EU
Sample 1 1000
Observations 1000

Mean	84.79500
Median	89.14147
Maximum	204.9934
Minimum	0.000000
Std. Dev.	42.46921
Skewness	-0.454848
Kurtosis	3.224259
Jarque-Bera	36.57668
Probability	0.000000

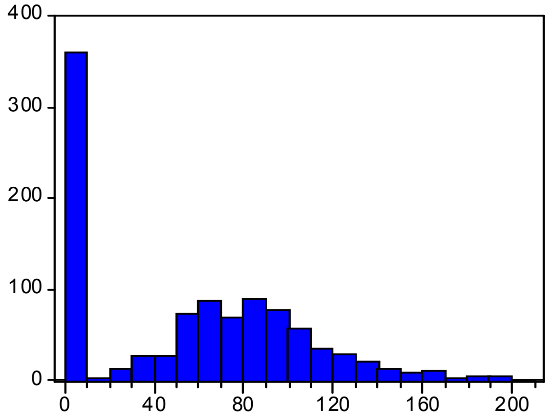
Figure 1-10: Distribution of Effective Carbon Tax 2040-2050 for the Rest of OECD



Series: REST_OF_OECD
Sample 1 1000
Observations 1000

Mean	73.66375
Median	81.07853
Maximum	204.9934
Minimum	0.000000
Std. Dev.	47.11739
Skewness	-0.193127
Kurtosis	2.438153
Jarque-Bera	19.36935
Probability	0.000062

Figure 1-11: Distribution of Effective Carbon Tax 2040-2050 for the Rest of the World



Series: REST_OF_THE_WORLD
Sample 1 1000
Observations 1000

Mean	54.90064
Median	60.20243
Maximum	204.9934
Minimum	0.000000
Std. Dev.	48.71756
Skewness	0.335142
Kurtosis	2.211675
Jarque-Bera	44.61410
Probability	0.000000

Table 1-4: Energy CO_2 Carbon Values in Euro99 per tonne of CO_2

	Mean	Median	Maximum	Std. Dev.	Skewness	Probability of no climate action	Carbon Value assesed to be exceeded with 5% probability
				EU - Energy CO2			
2005 - 2010	11	12	33	6.9	-0.3	0.23	21
2011 - 2020	17	18	51	9.5	-0.4	0.16	31
2021 - 2030	28	29	76	15.1	-0.2	0.14	53
2031 - 2040	45	48	119	21.9	-0.6	0.13	77
2041 - 2050	61	64	158	30.0	-0.5	0.13	108
2051 - 2100	85	89	205	42.5	-0.5	0.13	148
				Rest of OECD - Energy CO2			
2005 - 2010	2	0	26	4.4	2.4	0.76	13
2011 - 2020	7	0	39	9.2	1.1	0.56	25
2021 - 2030	16	14	73	16.3	0.6	0.43	45
2031 - 2040	29	33	97	25.2	0.2	0.37	68
2041 - 2050	48	55	152	33.7	-0.1	0.26	100
2051 - 2100	74	81	205	47.1	-0.2	0.22	143
				Rest of the World - Energy CO2			
2005 - 2010	0.01	0	4	0.2	18	0.99	0
2011 - 2020	0.54	0	29	2.6	7	0.91	3
2021 - 2030	3	0	73	8.7	3	0.78	22
2031 - 2040	11	0	90	18.2	2	0.66	51
2041 - 2050	27	15	142	30.4	1	0.47	79
2051 - 2100	55	60	205	48.7	0	0.36	134

The table above provides some summary statistics for the level of the effective carbon value derived from the Monte Carlo experiments for the three world regions with regard to the six time periods considered. A look at the table indicates that all three regions display decreasing carbon value volatility over the outlook. Starting from the EU region, it is noteworthy that as we move towards the end of the projection horizon, the ratio of the standard deviation on the mean carbon value persistently falls. With respect to the Rest of OECD region again the further the projection moves in the future, the lower the variability characterising the resulting carbon values relative to their magnitude, indicating the existence of diminishing uncertainty surrounding the growing participation of the Rest of OECD in the climate abatement effort led by the EU. Still, the carbon value estimates for the Rest of OECD countries display somewhat higher volatility over time compared to the respective EU estimates, a pattern which suggests stronger uncertainties surrounding the intensity and the mix of the eventual measures to tackle the climate change issue in the former region rather than in the latter. Finally, compared to the industrialised world, the Rest of the World countries display the lowest carbon value levels over time at the highest variability, demonstrating the weakest involvement and the higher uncertainty surrounding the involvement of third world countries in the international climate change policy process.

Figure 1-12 plots the skewness of the distribution of the effective carbon value and Table 1-5 below presents the correlation matrices of the carbon values across the three regions over time.

Figure 1-12: Skewness of distribution of effective carbon value

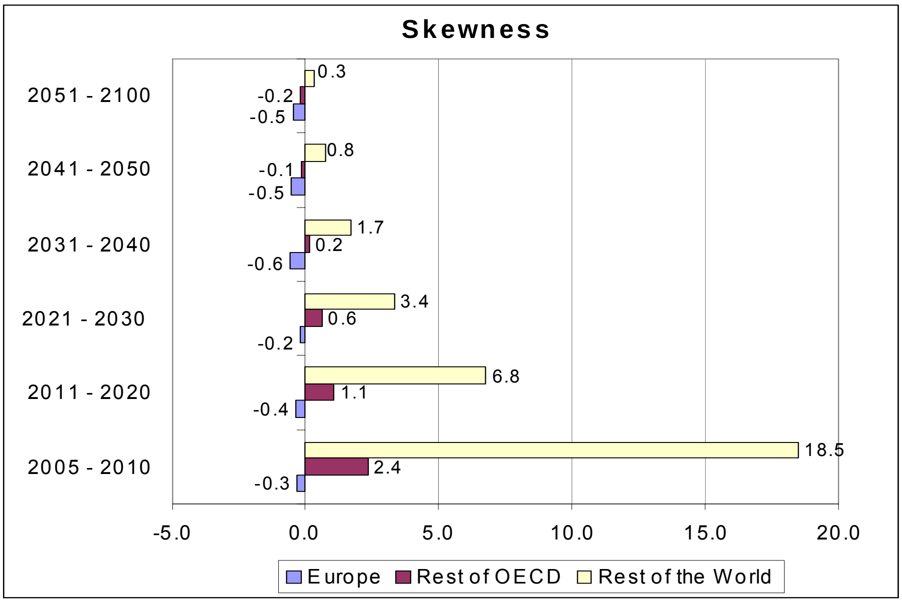


Table 1-5: Effective Carbon Value Correlation Matrix

2005 - 2010	EU	ROECD
ROECD	0.31	
ROW	0.00	0.08

2011 - 2020	EU	ROECD
ROECD	0.42	
ROW	0.12	0.29

2021 - 2030	EU	ROECD
ROECD	0.53	
ROW	0.23	0.44

2031 - 2040	EU	ROECD
ROECD	0.54	
ROW	0.28	0.51

2041 - 2050	EU	ROECD
ROECD	0.69	
ROW	0.40	0.58

2051 - 2100	EU	ROECD
ROECD	0.81	
ROW	0.62	0.75

The following paragraphs highlight the most notable observations arising from the previous tables:

- The distribution of the effective carbon value presents negative skeweness throughout the simulation period for the EU and positive for the Rest of the World. More specifically, the distribution of the EU carbon value presents limited but persistently negative skewness throughout the century, which indicates high probability for the region to outperform the mean expected carbon value (in line with the regions' leadership in the climate abatement effort) and minimal probability of introducing extremely low carbon values. In sharp contrast, the Rest of the World effective carbon value distribution presents positive skewness, which is particularly pronounced until 2030, seemingly related to this regions' rather 'volatile' definition of a carbon mitigation strategy. This positive skewness however is gradually reduced throughout the century, signifying that the estimated carbon values cluster at a relatively higher range on a decade-by-decade basis, a trend strongly illustrative of the anticipated increase in the participation from the Rest of the World countries to the climate abatement effort. A similar situation, albeit less pronounced, results for the Rest of OECD where the limited positive skewness in the carbon value probability distribution function steadily decreases over the years, falling to slightly negative values for the period beyond 2040, a pattern consistent with the closer alignment of the Rest of OECD to the EU climate strategy especially in the longer term.

- The effective carbon value correlations are increasing over time signalling the growing coordination of the abatement effort on a global scale for a successful international climate strategy. In general the EU and Rest of OECD regions present closely correlated carbon values, while the Rest of OECD and Rest of the World regions correlate to a lesser extent. Carbon value correlations appear least strong between the EU and Rest of the World regions in all periods considered; interestingly these two regions demonstrate even by 2050 a lower coordination of effort than what is projected for the EU and Rest of OECD regions already by 2020. The period 2031 to 2040 is of particular interest as it presents the minimum difference in the correlations of the Rest of OECD to the EU and the Rest of OECD to the Rest of the World carbon values; still the Rest of the World to the EU carbon values appear relatively independent. In all, the resulting picture in Table 1-5 suggests an increasing co-ordination of the Rest of OECD to the EU effort, and in turn of the Rest of the World to the Rest of OECD effort, which however never manage to equalise, not even in the very long term.

1.2.3. Summary Overview of Results

Some key results arise from the previous analysis regarding the future climate policy stance, as projected by experts participating in the SAPIENTIA project. More specifically the insight on the projected global allocation of the climate abatement effort can be summarised as follows:

- The reluctance to tackle climate change is projected to significantly decrease across the world. Even the third world countries which are not projected to undertake abatement policies until 2020, display intensive carbon mitigation effort thereafter, which becomes particularly evident after 2040 when this region is also projected to engage in relatively stringent climate policy.

- The EU will continue leading the world climate change abatement effort throughout the outlook, displaying the higher carbon value in all periods considered.

- A growing degree of coordination of the abatement effort on a global scale becomes evident. Indeed, the Rest of the World region is projected to increasingly participate in the Rest of OECD climate effort, which in turn presents an increasing coordination to the leading EU effort.

- All three regions are projected to display increasing mean carbon values over time which demonstrate decreasing volatility over the outlook period, patterns suggestive of the greater intensity and weaker uncertainty surrounding the eventual measures to tackle CO_2 emissions on a global scale.

- This gradual formation of an international climate change policy becomes particularly pronounced mainly after the third decade of the century, when the probability of no climate action across the world registers a sharp decline, giving way to an increasingly probable creation of a permit market across the industrialised world and -to a lesser extent- across the whole world. Still, the latter outcome remains confined to low probability values depicting the assumed reluctance of the Rest of the World countries to engage in equal to the industrialised world climate effort.

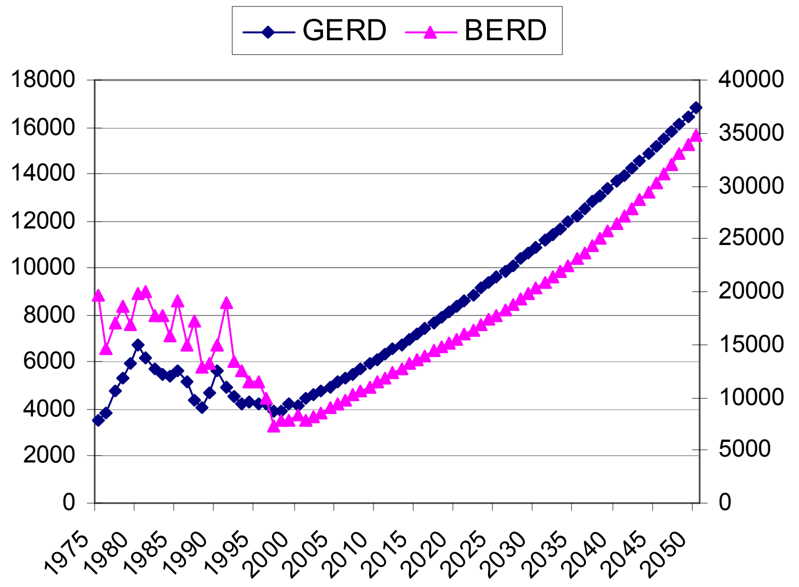
1.3. R&D Outlook

In order to equip the models participating in the SAPIENTIA project with reasonably harmonised learning mechanisms, ICCS-NTUA has undertaken the estimation of Two Factor Learning Curves to be shared by the models (see Part B). The use of TFLCs presupposes the availability of values for both capacity and R&D, either through model mechanisms or endogenously. Most models in SAPIENTIA generate values for capacity/technology take-up endogenously. Very few, however, include endogenous mechanisms for determining R&D expenditure on specific technologies. For this purpose, it was necessary to elaborate an outlook for R&D effort directed to different technological options, to be used as a common assumption for the construction of the reference cases of the different models. This Outlook is based on past trends, recent changes in emphasis and perspective analysis based on judgement, but does not intend to be the result of rigorous modeling logic. On the other hand, effort was devoted to maintain some consistency in order to allow a clear picture on a probable direction of future R&D to emerge.

Inevitably, predicting the future size and direction of R&D is a highly speculative activity, especially for such a long-term period, however every effort has been made here to adequately present the underlying assumptions and causal mechanisms that are expected to drive the projected developments in the energy technology system. The baseline projections presented below are based on critical socioeconomic and geopolitical assumptions which indicate that the recent economic downturn -which was followed by slackening markets as world GDP and with it electricity generation growth slowed down- will be reversed, that globalization will continue, that primary energy resources will become relatively less abundant, that concerns with security of energy supply shall remain and that dealing with climate change will retain its place at the top of the environmental and political agenda.

In the sequel, the trajectories of the Government Energy Related R&D (GERD) and Business Energy Related R&D (BERD) Outlooks on 38 technologies for the period to 2050 are outlined. The general shape of the outlook has been based on the neutral assumption that both Government R&D and Business R&D will grow proportionally with GDP, for the years succeeding 2003. This assumption results in a reversal of the recent downward trend, which is particularly eminent in the late 80's and 90's, and leads to a substantial growth in R&D on energy related technologies for the next 45 years.

Figure 1-13: Total R&D in M€99 excluding vehicle engines (BERD is displayed on the right axis)



The figure above illustrates this trend. The picture for GERD and BERD appears highly contrasted until the beginning of this century. BERD shows a slow drop in real terms with considerable variations in the first years of the period considered, until the early 90's when a precipitous decrease takes place which holds until the end of the decade. GERD on the other hand shows an increase in absolute terms during the first years of the period considered and until the early eighties, followed by a persistent decline throughout the eighties, which with the exception of the years 1988-1990 is evident until the end of the nineties. This situation however is completely reversed in the forecast, as both BERD and GERD follow an upward trend, with an average annual growth rate of around 2 percent per annum for the whole period to 2050. Compared to recent history the forecast clearly represents considerable R&D effort, signaling an R&D intensive future.

1.3.1. Government Energy Related R&D (GERD)

The growth pattern of the public R&D budget during the seventies can be mainly explained as an answer to the challenges posed by the oil shocks, which triggered large public energy R&D

programmes. As a result, total GERD more than doubled during the second half of the seventies, from 3 billion euro (€99) in 1975 to more than 6.5 billion in 1980. This growth pattern however was followed by a sharp downturn, particularly evident until 1988, a development which can be largely attributed to the reversal of the US R&D policy (project independence). With the exception of the two final years of the eighties, GERD continued its declining trend until the end of the century, which led to a total spending of slightly above 4bn in 2000, while the forecast projects that GERD will reach and surpass its 1980 level only after 2012.

Figure 1-14: Government Energy R&D in MEuro99.

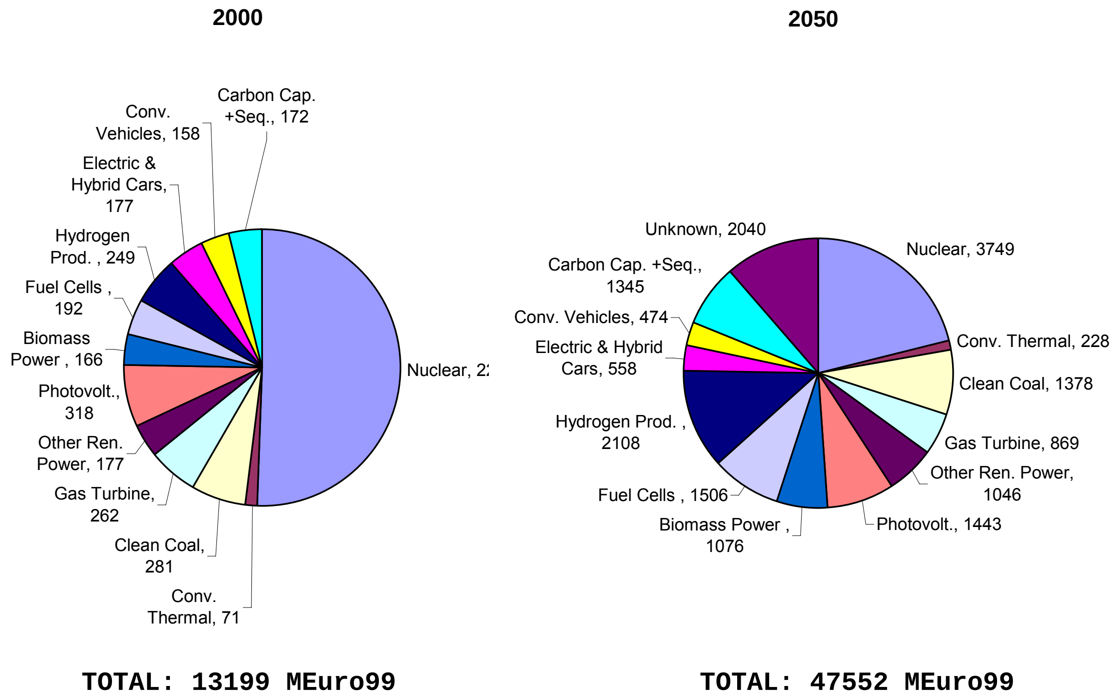


Figure 1-14 above and Figure 1-16 below correspond to the disaggregation of the total Government Energy R&D and Business Energy R&D to 12 clusters of technologies. A crucial element of the R&D outlook derives form the assumption that an unknown technology attracting gradually but increasingly additional R&D expenditure will emerge from mid two thousand twenties onwards. This assumption was made in order to avoid excessive concentration of R&D effort on a few technologies after support of more conventional technologies tapers-off. Apart from that, failure to include such an option would lack realism (there is bound to be unknown alternatives emerging in such a long period) and second would imply diminishing returns on future R&D effort which would in turn result in an overall R&D productivity and efficiency reduction.

Figure 1-14 presents Public energy R&D shares on key groups of technologies as realised in 2000 and their outlook for the year 2050. A preliminary comparison indicates that important changes occur in the technology-mix at world level between the years 2000 and 2050. The 2000 public R&D budgeting is dominated by nuclear technologies. Indeed, nuclear R&D expenditure amounts to slightly above half the total Government R&D spending. Various factors have contributed to this. First nuclear research programmes address issues of nuclear safety which are increasingly becoming a public concern thus threatening the very future of nuclear power in the energy system. Moreover projects aiming at the decommissioning of the nuclear plants and the general issue of a permanent solution to the radioactive waste disposal problem account for a large portion of recent nuclear research. In general, public research designated as “nuclear research” or “nuclear fuel cycle” may to some extent correspond to improvement activities of electricity generation reactors, however, most research has been directed to the above mentioned issues, rather than to the direct reduction of the nuclear energy production costs. Turning to the outlook however the overall picture appears highly contrasted. Nuclear power research in 2050 is projected to receive an amount equal to three times its respective 2000 funding in absolute terms; however its share in total GERD declines sharply from over 50 percent in 2000 to only 21 percent in 2050. Recent trends indicate that an increasing part of additional nuclear R&D funding will be devoted to the development of the technical and economic characteristics of the fourth generation reactors.

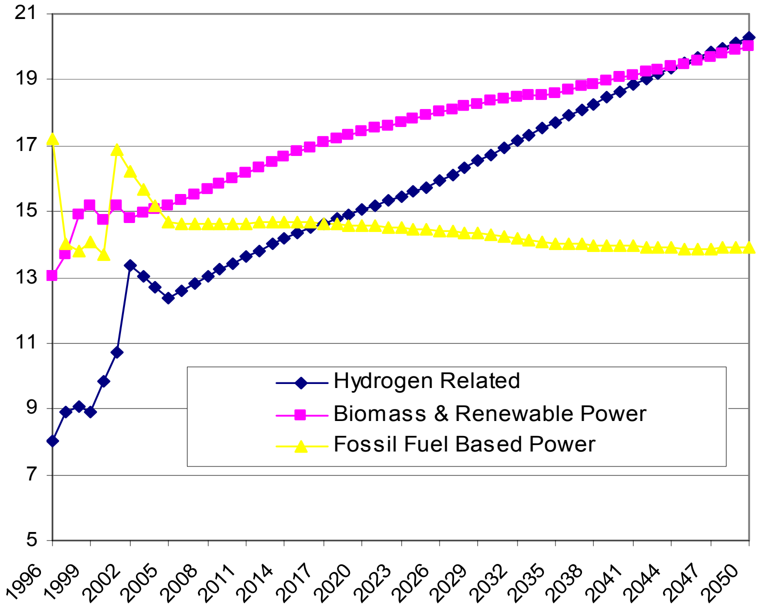
On the other hand Renewable energy technologies maintain lively R&D interest throughout the forecast period. For the year 2000 these technologies absorb a total of 661 MEuro(99), representing a share of about 14.7% of total GERD. Photovoltaic research accounts for the largest portion with a spending of about 318 million €99, corresponding to a share of above 7% of total GERD i.e. almost equal to wind, solar, hydro and biomass research together. Photovoltaics, addressing a 'niche market', attract nearly 50% of the Government R&D budget directed towards renewable technologies, experiencing high growth rates in recent years. Wind, having experienced important technical improvements and cost reductions through sustained previous government R&D funding, has moved into full commercialization and its improvements are now driven mostly by business R&D.

Government R&D interest towards Renewable technologies is maintained over the outlook period. In absolute terms, the overall amount of GERD directed to Renewables sees a fivefold increase, representing over 20 percent of the total 2050 GERD. Interestingly, Biomass Power appears with the highest relative increase in GERD expenditure, with a share rising from 3.6% in 2000 to 6.0% in 2050 while Photovoltaics are still privileged with the largest portion in GERD (8.1%) among other renewables.

A notable feature of the outlook is the reduction in the shares of almost all conventional technologies matched by a shift of the research interest towards hydrogen related technologies. The reason for this evolution is twofold. With regard to the former, conventional technologies have good prospects and little uncertainty about them nowadays. Accordingly, their potential is likely to saturate as they attract increasing R&D funds over the coming years. By 2050 they may no longer represent a "mature technology"- in the habitual sense- but an "ageing technology", for which R&D effort dissipates. Secondly, R&D programmes targeting technology improvements, cost reductions and enhanced market penetration of the 'novel', promising hydrogen related technologies, accelerate the transition process from pilot to market technologies by 2050. This R&D intensive outlook for Hydrogen production technologies, Fuel Cells as well as carbon capture and sequestration technologies results in a doubling of their share in GERD from 2000 to 2050. Hydrogen production technologies experience the most radical increase, from 5.5% in 2000 to 11.8% in 2050, followed by Fuel Cells (from 4.2% to 8.4%) and CO_2 capture and sequestration technologies whose aggregate funding sees an eightfold increase, translating into a 3.7% share increase. Government R&D on Carbon capture and sequestration technologies is projected to focus on the CO_2 sequestration process. This increase in research intensity on carbon reducing options underlies a projected increase in the concern on climate change issues.

Finally, Figure 1-15 below summarises the public R&D profiles for three major technology groups: Hydrogen Related, Biomass and Renewable Power Related and Fossil Fuel Based technologies for the years 1996-2050. The portfolio profiles of the first two technology groups display marked similarities, especially with regard to an almost constant upward trend. In the short term, Hydrogen related technologies receive less than half the amount of GERD directed to Fossil Fuel technologies, whereas in the longer term they find their own growing share, complementary to Biomass & Renewable power technologies in a growing effort towards a cleaner, carbon-free environment. GERD on Hydrogen Production and Fuel Cells technologies is projected to increase substantially throughout the 1996-2050 period, suggesting in a way that cost reductions in these technologies are likely to become pronounced, enhancing their market penetration. In contrast, the projected diversion of public funds away from fossil-fuel technologies squeezes out their budget shares which after a sharp decrease in the first years of the period considered, continue with a smooth downward pattern, managing however to stabilise over a threshold value of about 14% of total BERD by 2050.

Figure 1-15: Outlook of shares in GERD

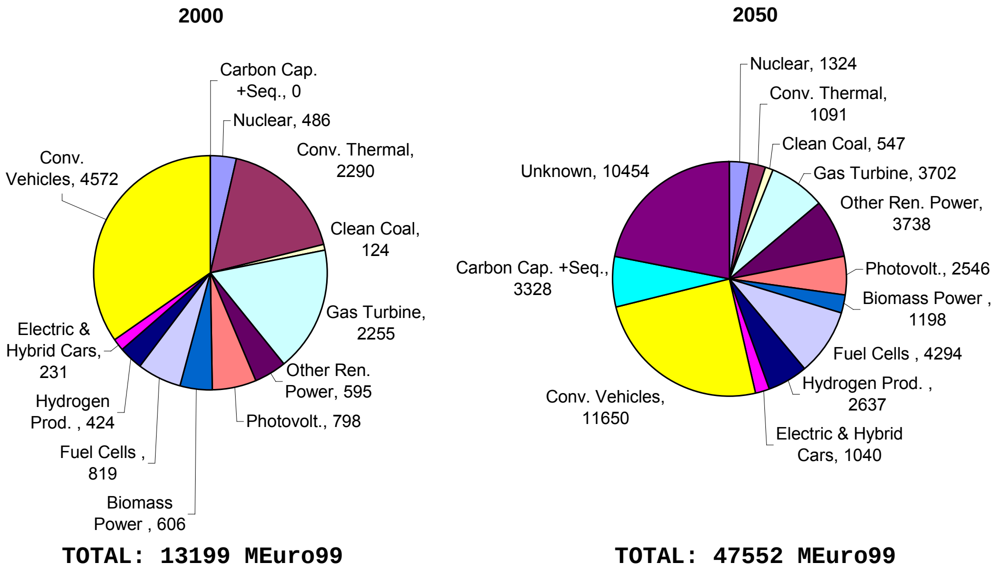


1.3.2. Business Energy Related R&D (BERD)

Figure 1-16 below shows the Outlook for Business Energy R&D expenditure with respect to 13 (including the unknown technology) technology clusters.

A cursory look at Figure 1-16 with focus on the 2000 R&D profile indicates the predominance of the Conventional Vehicle technologies. Indeed, these absorb over a third of total Business Energy R&D in 2000 which falls to around one quarter by 2050. The reason for this considerable channeling of Business R&D towards the conventional automobile sector is that this sector constitutes a huge market and technical developments are an essential factor for auto manufacturers to maintain profitability. The auto market is one of the most competitive, fast growing worldwide markets. Accordingly, the main bulk of the privately funded research on this sector is directed towards technical improvements-efficiency and environmental performance- and towards the enhancement of the attractiveness of the vehicles.

Figure 1-16: Business Energy R&D in MEuro99



A striking feature of the 2000 R&D portfolio is the absorption of a large share of BERD by fossil fuel based technologies –such as conventional thermal (17.3%) and Gas Turbine (17%) technologies. This pattern is largely attributed to retrofitting activity in the power industry, especially in Non OECD countries. Turning to the outlook the aggregate share of these technologies drops dramatically from almost 34.4% in 2000 to 10% in 2050 as most of the plants concerned have either been retrofitted or decommissioned and replaced by new types of plants. Conventional thermal technologies are the ones facing the most dramatic drop in their shares, from 17% to only 2.3% in the outlook.

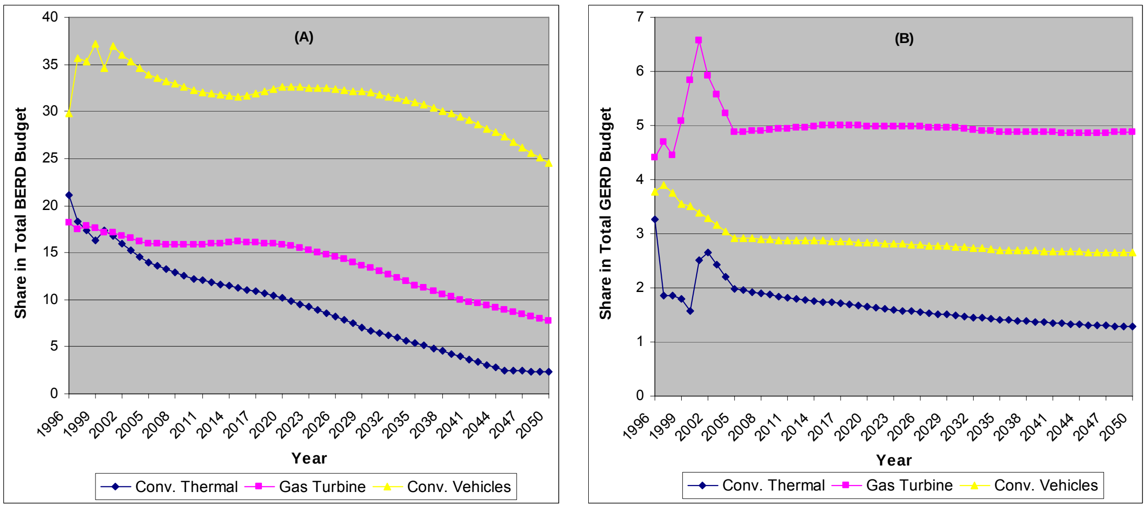
In fact the picture in 2050 appears entirely reversed, with conventional technologies losing share to technologies that attracted small shares in 2000. Again the most notable example of this category are Carbon Capture and Sequestration, Hydrogen and Fuel Cell technologies, which are projected to experience a significant rise in shares in private R&D throughout the first half of the century. More specifically CO_2 Capture and Sequestration technologies not only manage to acquire a place in private R&D budgeting but also tend to occupy a relatively privileged position in the ranking of options reaching a share of about 7% in BERD in 2050. Likewise, Fuel cell and Hydrogen production technologies are projected to experience a fivefold to six fold increase in private R&D between 2000 and 2050, which translates into shares in BERD of about 9% and 5.5% by 2050 respectively.

Renewable technologies display a contrasted picture; Biomass power technologies and photovoltaics find their weights in private R&D portfolio decreased over the outlook, from 4.5% and 6% in 2000 to only 2.5% and 5.3% by 2050 respectively. On the other hand, other renewable technologies (in particular Wind Offshore technologies) are projected to benefit from substantial private research, receiving by 2050 R&D funding equal to six times the 2000 level, which translates into a 3.3% share increase over the period considered.

1.3.3. Comparative Outlook of shares in Government and Business Related R&D for some key technologies

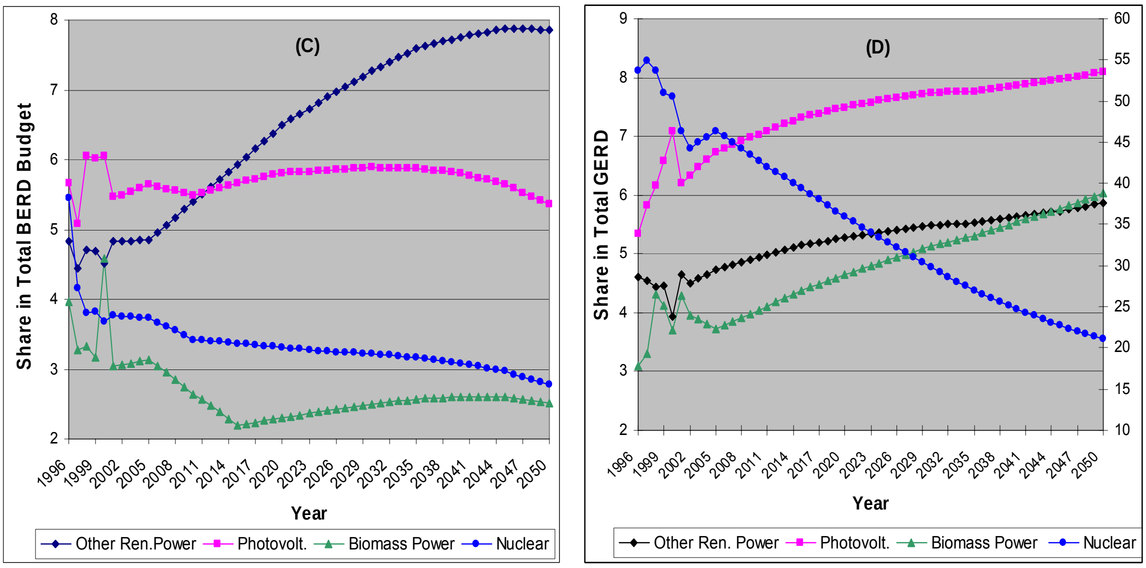
Figure 1-17 to Figure 1-20 below present in greater detail the private and public R&D development paths for some key technology categories for the years 1996-2050. A cursory look at Figure 1-5, points to the initial high degree of private R&D commitment in favour of the key conventional vehicle and thermal technologies, as these absorb almost 50% of the private manufacturer R&D effort in the initial years of the period considered. As potential improvements in these technologies peak, interest in them will start declining and the prospects for these technologies are likely to be revised downwards, influenced by an anticipated decline in the marginal productivity of R&D for them. Accordingly, the private R&D share directed to conventional vehicle and thermal technologies is projected to follow a strongly declining trend until the final year of the projection period. This is also the case for GERD, where both these technologies are projected to absorb a decreasing share of the Government R&D for the years following 2005 and until the end of the projection period. In the GERD outlook however, conventional thermal and vehicle technologies maintain over time a very low degree of commitment in terms of GERD and contrary to their outlook in BERD, the public R&D shares for these technologies follow a relatively gently decreasing path until 2050.

Figure 1-17: Business and Government Energy Related R&D by technology category



Turning to another of today's 'winning' technologies, i.e. gas turbines, Figure 1-17(A) also illustrates a gradual abandoning of private interest in R&D investment but this takes place only after 2015. Until then, this technology performs well, displaying a fairly steady and relatively high BERD path. This pattern can be largely attributed to the increasing accumulation of R&D effort on gas turbines, stimulated by both private and public budgeting policies over time. This increasing accumulation of R&D in gas turbines is projected to shift this technology to a more mature phase, thus reducing the expected productivity of additional research and with it future R&D spending, mostly from private capital. Public R&D on gas turbines on the other hand is projected to remain constant, at a level of around 5% over time.

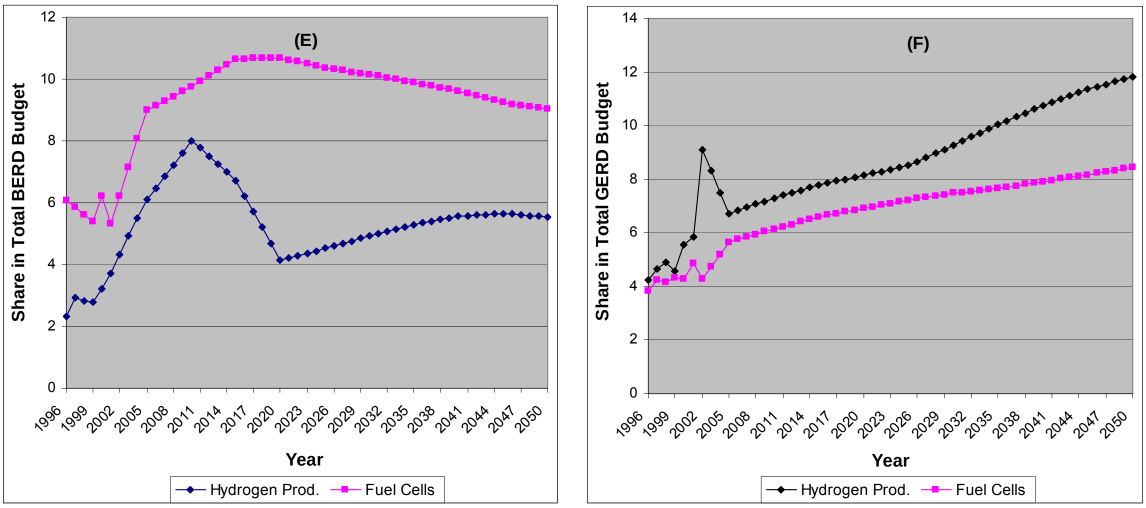
Figure 1-18: Business and Government Energy Related R&D by technology category [in 1-6(D) Nuclear Power is displayed on the right axis]



Turning to non-fossil technologies, private research for some renewable technologies is projected to increase regularly throughout the period, with Wind Offshore technologies being the main beneficiary of this intense R&D activity. The projection indicates that this technology will account for slightly less than half the total private R&D budget for other renewable technologies by 2050. GERD on the other hand, is mostly directed towards Solar Thermal Power plant technologies, which are also projected to reach a share of 46.5% in the public budget for other renewables by the final year of the projection. The remainder of the budgets is mostly directed to wind technologies in the case of GERD, and wind and small hydro technologies in the case of BERD, all of which however experience a strong decline over the outlook period. With regard to Biomass Power and Photovoltaic technologies however, the projection incorporates a declining interest of private R&D budgeting towards these options, which is opposite to the growing support that these technologies receive in terms of public R&D funding. In specific, Biomass Power technologies feature a sharply declining path in BERD, until 2015, which is however reversed in the subsequent years, displaying a gently increasing pattern until 2050. On the other hand, the share of these technologies in BERD is projected to fall by 1.5% between 1996 and 2050, whereas over the same period, the ever-increasing commitment towards Biomass technologies from GERD results in a doubling of their share (from 3.1% to 6.0%).

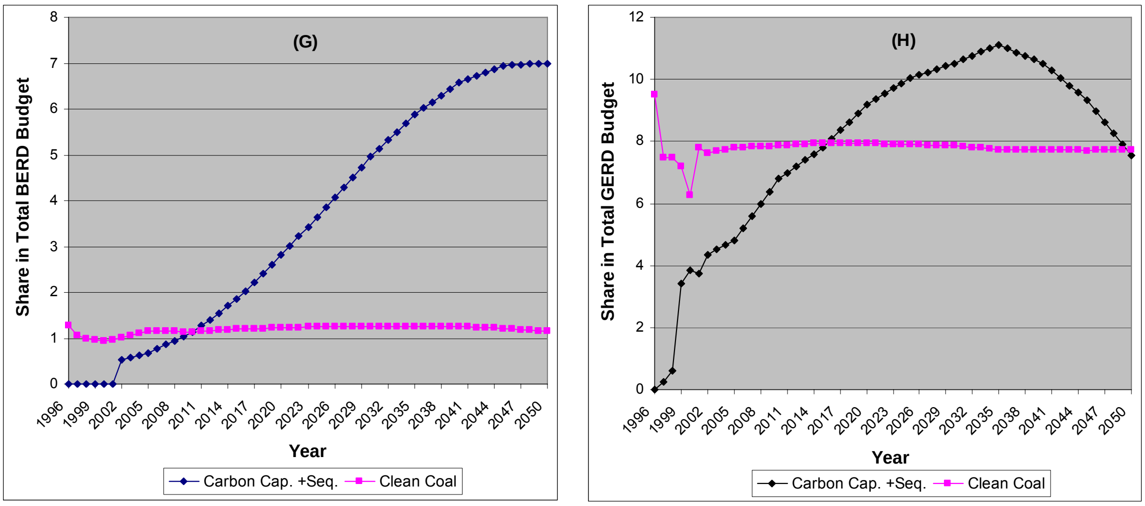
The weight of Photovoltaic technologies in the Business R&D portfolio is projected to stabilise at a rate of around 5.6% until 2010, slightly increase in the subsequent years, reach a peak at around 2030 and then start progressively declining until 2050. The overall trend results in a 0.7% decrease in their share between 1996 and 2050 (from 6% to 5.3%). The reverse effect applies for Photovoltaic technologies in the Government R&D outlook, where a substantial increase of their share in GERD is projected (from 5.3% in 1996 to 8.1% in 2050), illustrated in an ever-increasing path throughout the projection period. Finally, contrary to the dominant place of nuclear power in the public R&D budget, this technology is limited to low shares in BERD over time. During the period considered, private research on nuclear power amounts to only 5.5% of BERD in 1996, features a sharp decline until 2000, while the outlook indicates a fairly steady path, albeit in a slightly downward trend, until 2050, when nuclear technologies are projected to receive a share of only 2.7% in BERD. In sharp contrast, nuclear power technologies demonstrate a 53.8% share of GERD in 1996 which falls by almost 10 percentage points by 2005, while the outlook projects a sharply decreasing path until the final year of the projection, when it reaches a value of 21% in total government R&D.

Figure 1-19: Business and Government Energy Related R&D by technology category



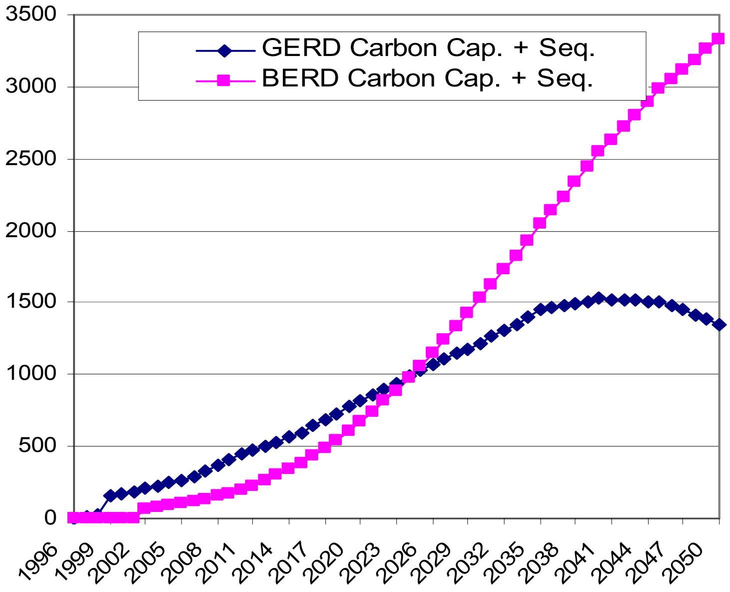
With regard to hydrogen related technologies, Figure 1-19 in combination with Figure 1-15 clearly illustrate the gradual increase in interest on the prospects of a future hydrogen-based energy system. Hydrogen production and Fuel Cell technologies are projected to receive substantial and sustained public R&D effort throughout the forecast period, illustrating the attractiveness of these technologies, especially as some of the initially high return, full capacity technologies progressively start to exhibit diminishing marginal productivity. As a consequence of this sustained public R&D effort, these technologies become in the longer term increasingly attractive for the private sector as well. By 2050 the private sector is projected to direct 9% of its total R&D budget to Fuel Cells and 5.5% to Hydrogen production technologies, whereas the corresponding shares for the public sector rise to 8.4% and 11.8% in total GERD.

Figure 1-20: Business and Government Energy Related R&D by technology category



Finally, Figure 1-20 (G) outlines the private R&D path for CO_2 Capture and Sequestration technologies, which is projected to follow a persistently increasing trend over time as these technologies tend to occupy an enhanced application and market penetration potential, conditional on the anticipated cost improvements. The research interest from the private sector is projected to concentrate on the CO_2 capture procedure, whereas public R&D is expected to focus on the development of carbon sequestration methods. Figure 1-21 below illustrates in somewhat greater detail the growth patterns of carbon capture and sequestration technologies from both the public and private point of view. Business R&D displays an ever increasing interest towards these technologies, whereas Government R&D displays a similar path until 2040, when a reversal is projected. Both patterns however clearly suggest that climate change issues and CO_2 abatement efforts will receive increasing concern in the future, hence technologies conducive to this effort will essentially ‘force’ their ways into high places of the future R&D ranking.

Figure 1-21: GERD and BERD on Carbon Capture and Sequestration (MEuro99)

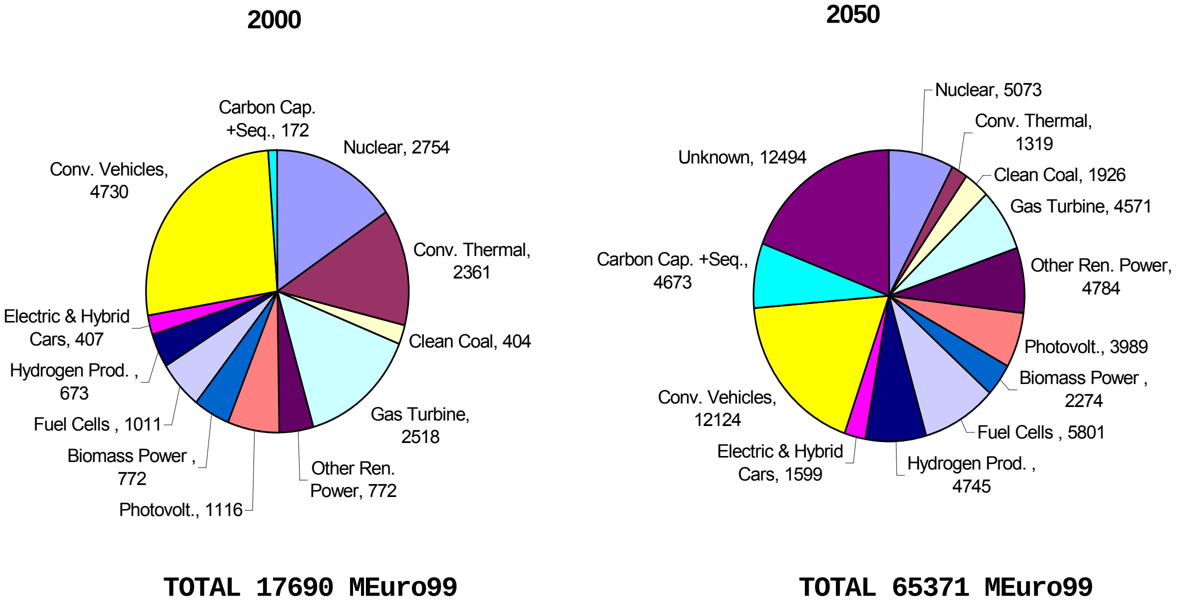


1.3.4. Total Energy Related R&D

The distribution of the total R&D budget between the technology groups under consideration here is illustrated in Figure 1-22. The predominance of Conventional Vehicle technologies for both the

2000 and 2050 R&D profiles (excluding the share of the unknown technology in the latter) is pre-eminent; nevertheless their share faces a marked decline from a total of 26% in aggregate R&D budget for 2000 to only 18% for 2050, a development which reflects the sharp decrease of the share of conventional technologies in private R&D. Conventional thermal technologies are the least favoured in the outlook, as they experience a dramatic decline not only in relative terms but also in absolute terms; their share in total R&D falls from 13.3% in 2000 to only 2% in 2050 whereas the total amount of R&D directed to them is less than half in the outlook. Nuclear technologies face a halving of their share in the outlook which can be attributed to the withdrawal of the R&D support directed to them by the public sector, coupled with the failure to attract any private interest in the forecast. Finally, gas turbine technologies, which face a 7.2% drop in their share by 2050, exhaust the list of todays most privileged, in terms of R&D technologies which are however projected to experience an important decline in their R&D shares over the outlook period.

Figure 1-22: Total R&D in MEuro



Budgets for Photovoltaics, Electric and Hybrid cars and to a lesser extent Biomass and Clean Coal technologies display the most stable path over the projection period. Among these only Clean Coal technologies manage to maintain a moderate interest of both private and public R&D over the outlook, displaying a fourfold increase in absolute value by 2050, which however translates into a slight share increase (0.1%). Photovoltaics and Biomass Power are projected to experience a 0.2% and 0.9% decline in their shares respectively, which can be attributed to declining private interest despite the projected commitment to these options from public R&D financing. The reverse effect operates on Electric and Hybrid cars which are projected to encounter a reduction in their public R&D share by 2050, which is however balanced by the increasing interest on behalf of private agents, resulting in a moderate increase in their share (0.1%) by the final year of the projection.

A key feature of the outlook derives from the projected intensification of CO_2 emission reduction efforts, which take the form of substitution away from carbon intensive technologies in favour of low carbon or non-fossil technologies. Accordingly, some Renewable technologies along with technologies conducive to CO_2 abatement efforts, such as Carbon capture and sequestration technologies receive intensive R&D funding from both private and public budgets, which results to an increase in their total R&D shares by 2050. With regard to the former, total R&D expenditure on other renewables increases by almost 3%, favoured by considerable R&D effort from both Government and Business R&D over time, especially towards technologies such as Wind, Wind offshore or Solar Thermal. CO_2 capture and sequestration technologies experience a sharp share increase, which can be apportioned to both the large private funds towards CO_2 capture technologies and the intense public R&D support to carbon sequestration technologies.

Finally, Fuel cells and Hydrogen related technologies are also projected to receive intensive R&D effort from both public and private budgets, experiencing a share increase of about 3.2% to 3.5% respectively by 2050.

1.3.5. Conclusions:

With regard to both private and public R&D allocation trends, some general remarks can be made:

- Fuel Cells, Hydrogen production and CO_2 carbon and sequestration technologies are the winning technologies in terms of both private and public R&D effort, experiencing a take off in their shares from the beginning of the century followed by a consistent increase until the final years of the projection. This projection clearly points to a marked future shift of R&D interest on today's relatively unexplored options while the accumulation of R&D funding over the years will most likely translate into cost performance improvements and hence larger market penetration for these technologies.
- Renewable technologies manage to maintain their share in total R&D in the Outlook. The forecast indicates that the projected decrease in the shares of both Photovoltaics and Biomass Power is eventually outweighed by the relatively strong research activity on other renewable energy technologies such as Small Hydro, Solar Thermal Power Plant and Wind Offshore technologies, which receive substantially higher R&D effort, mainly originating from private budgets.
- R&D investment on conventional technologies is projected to be markedly lower from both the public and private point of view, while conventional thermal and vehicle technologies see their private funding shares deteriorating throughout the projection period. The projected diversion of funds towards non-fossil technologies also explains the downward future path followed by today's leading gas turbine technologies.
- A substantial shift in public R&D funding away from nuclear technologies is projected coupled with a consistent failure to attract private interest in the forecast. This abandoning of nuclear power R&D can be largely explained by the fact that this technology, albeit it is a non-fossil power form and susceptible to large scale development, is suffering from a very high R&D cost for even modest cost performance improvements.

2. Outlook Using the ERIS Model

One critical factor affecting long-term sustainability, including climate change mitigation and maintaining security of energy supply, and also expected to affect the impact of policies aimed at achieving sustainable development, is the likely trajectory of energy-system development without additional technology policies. The extent to which the baseline scenario of the evolution of the energy system is fossil fuel intensive, or reliant on new technologies, has a large bearing on the potential impact of additional technology policies on indicators of sustainable development. Importantly, however, it is not necessarily a simple linear relationship. For example, additional public or private support for key low-emissions technologies may have little impact when the future is dominated by either incumbent technologies, which enjoy enormous competitive advantages, or low-emissions technologies that become successful regardless. Instead, it is in those cases where technology choice is finely balanced, or where the timing of market penetration is critical to the long-term success of a technology, that technology support can be most effective in realising sustainable development. The baseline scenario can provide some indication of where potential targets for technology policy support may arise.

2.1. Policy baseline

2.1.1. Climate policy

In this baseline scenario we do not make the unrealistic assumption that no efforts are made over the next 100 years to mitigate the risks of climate change. Rather, we assume that all world regions implement greenhouse gas abatement policies and measures at some point during the 21st century, although at different times and rates depending on regional circumstances. Moreover, these abatement policies are assumed to be independent of the potential technology policies explored in the SAPIENTIA project. The climate change mitigation policies and measures are represented in a stylised way in the baseline scenario in the form of taxes on greenhouse gas emissions. In reality, world regions are likely to adopt an array of abatement measures, and the use of a GHG tax in the baseline scenario merely seeks to represent the effective stringency of all of these measures. The GHG tax rates assumed in this scenario and applied to the six main gases are presented in Table 2-1.

Table 2-1: GHG tax rates (€/tonne carbon equivalent) assumed under the baseline scenario

	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Europe	0.00	14.00	21.00	33.30	50.50	70.70	98.60	98.60	98.60	98.60	98.60
Rest of OECD	0.00	7.60	12.60	22.80	37.90	56.90	83.80	83.80	83.80	83.80	83.80
Rest of World	0.00	1.40	3.60	9.20	19.40	34.30	62.20	62.20	62.20	62.20	62.20

Source: SAPIENTIA Delphi analysis.

2.1.2. R&D policy – public and private

Another critical feature of this scenario is the assumed future energy R&D investment budget and distribution across the portfolio of competing energy technologies. The R&D investment outlook, including the allocation to different technologies is described in Part D1a(iii) [of the SAPIENTIA final report], and this is used to develop the baseline described below. Importantly, future R&D budgets and expenditure patterns are highly uncertain, and as part of this analysis we explore this uncertainty by also examining extremely optimistic and pessimistic scenarios of future R&D. The results of this sensitivity analysis are presented in Part D-2.

Firstly, however, we examine a number of salient characteristics of the baseline scenario.

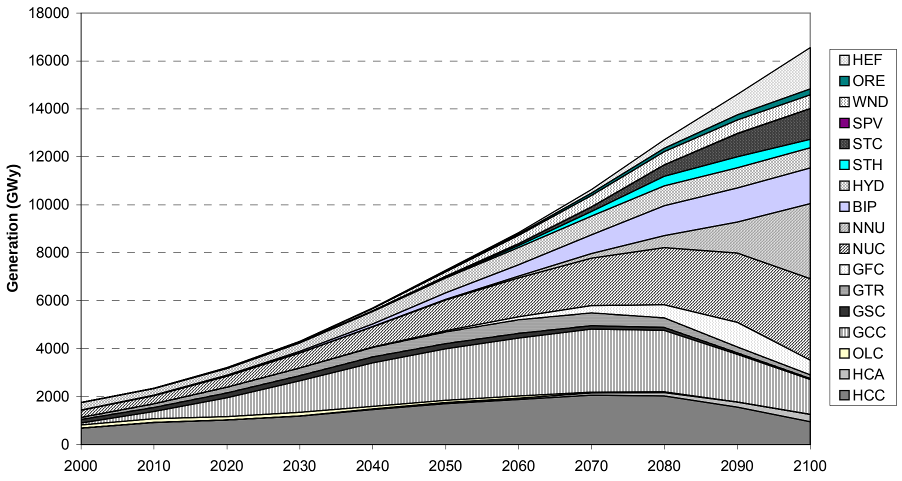
2.2. Detailed description of baseline scenario results

2.2.1. Technology uptake and adoption

In the context of examining the potential for different technologies to contribute to sustainable development, it is useful to examine technology choice in the main energy sectors under this baseline scenario. Accordingly, we show in Figure 2-1 the uptake of different electricity generation technologies under the baseline scenario over the 21st century.

The most noticeable transition across the century is the declining share of fossil fuels in electricity generation, particularly from coal, which is not surprising when one considers the imposition of GHG taxes assumed in this scenario. However, in absolute terms generation from both coal and natural gas increases until mid-way through the second half of the century, and generation from IGCC coal and gas fuel cell generators is still increasing in 2100. The decline in aggregate generation from fossil fuels coincides with an increase in generation from nuclear (both 3rd and 4th generation) and renewable sources of energy. A diverse mix of renewable generators is supported by resource constraints and niche markets, with no clearly dominant technology, although solar photovoltaics appear to be restricted to very small niche markets. Along with 4th generation nuclear power plants, hydrogen-fuelled stationary fuel cells are among the fastest growth generation technologies at the end of the century. Accordingly, if we look across the whole century, the dominant sources of global generation shift from: conventional coal, nuclear and hydroelectric generation in 2000, to; gas combined cycle, conventional coal and nuclear in 2050, and finally to; conventional and advanced nuclear, and hydrogen fuel cell generation in 2100.

Figure 2-1: Global electricity generation mix, baseline scenario (with GHG abatement policy)



Note: Technology abbreviations are as follows: HCC: conventional coal, HCA: advanced coal (IGCC), OLC: oil conventional, GCC: gas combined-cycle, GSC: gas steam cycle, GTR: gas turbine, GFC: gas fuel cell, NUC: nuclear conventional, NNU: new nuclear, BIP: biomass gasification, HYD: hydro, STH: solar thermal, STC: solar thermal cogeneration, SPV: solar photovoltaics, WND: wind turbine, ORE: other renewables, HEF: hydrogen fuel cell.

The continuing dominance of fossil fuels mid-way through the 21st century, even under a baseline scenario that includes climate change mitigation policies, illustrates the inertia of energy systems, particularly the time taken for new technologies to become competitive and penetrate the market on a large scale.

Although an increasingly important part of the global energy system under this scenario, electricity generation is only one of a number of energy sub-sectors in which technological change may substantially transform production. In Figure 2-2 we present the development of the subsector representing other forms of secondary fuel production, which is currently dominated by oil refining. In this subsector, oil refining continues to play a dominant role throughout much of the century, and total combined output of other fuels from new energy production technologies only surpasses petroleum output after 2080 (as shown in Figure 2-2). These new energy production technologies comprise hydrogen synthesis technologies based on steam reforming of natural gas, pyrolysis of biomass and partial oxidation of coal. In this baseline scenario, penetration and uptake of biomass- and coal-based hydrogen synthesis technologies is relatively rapid in the second half of the century, and total hydrogen output in 2100 is roughly equivalent to refinery throughput in 2000. The fact that coal-based hydrogen production is supported may initially seem surprising when one considers the impact of a GHG tax, but occurs nonetheless because it represents a more efficient way of utilising the energy in coal where the resulting hydrogen is used in a fuel cell, and more importantly, is amenable to carbon capture. Synthesis of hydrogen via reforming of methane is not attractive, mainly because gas is already a relatively low-emissions and flexible energy carrier.

Figure 2-2: Global fuel conversion, baseline scenario (with GHG abatement policy)

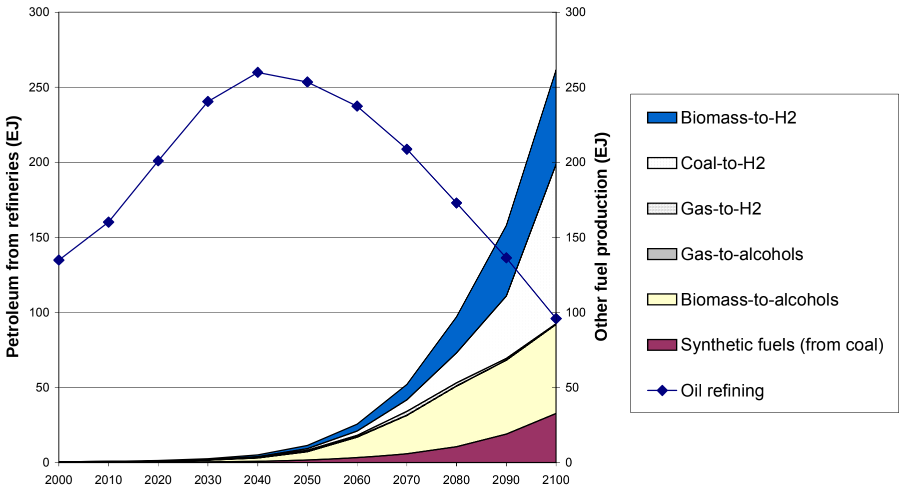
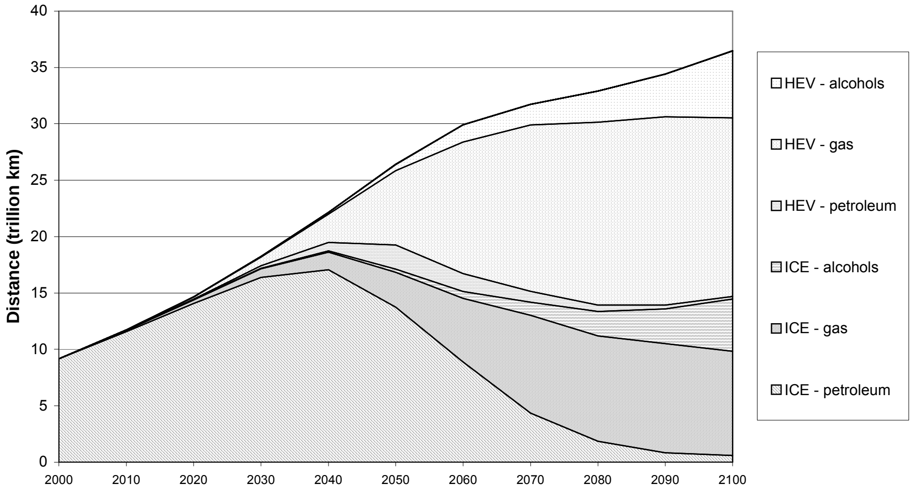


Figure 2-2 shows that the other fuel production technologies that achieve significant market penetration include Fischer-Tropsch liquids synthesis and alcohol production from biomass. The attraction of Fischer-Tropsch liquids from coal is partly explained by the declining availability and depletion of oil resources, and the potential to capture some of the carbon in the coal feedstock. Biomass-to-alcohol synthesis technology, on the other hand, is attractive because of it represents a zero-emissions fuel that can be distributed and used without the need for extensive and expensive new infrastructure or adoption of new vehicle technologies.

The other main sector of interest is transportation. The choice of vehicle technologies under this baseline scenario is illustrated in Figure 2-3, which presents the total travel distance accounted for by different passenger car technologies over the 21st century. The assumptions applied here result in an initially gradual transition away from the conventional petroleum ICE vehicles to natural gas-fuelled vehicles – both conventional ICE and hybrid electric-ICE vehicles. However, between around 2040 and 2060, the gasoline ICE vehicle is displaced as the dominant transport technology, and replaced by the gas hybrid. Hybrids continue to play a dominant role in the transport market for the remainder of the century, although the cost premium of the technology ensures that it is unable to achieve a market share of much more than 60 percent. The increasing availability of zero-emissions alcohol fuel in the second half of the 21st century result in the gradual penetration of this fuel into both the hybrid and conventional ICE market, and the availability of relatively cheap natural gas in some world regions also ensures that the conventional ICE technology maintains a significant market share, even though gasoline plays almost no role by 2100.

Figure 2-3: Global technology and fuel choice for passenger car travel, baseline scenario (with GHG abatement policy)



The only other energy-related technologies that we will mention here are those for carbon capture and storage (CCS). These technologies are attractive under this scenario, and by 2100 around 2.0 Gt of carbon are captured annually (which is close to 14 percent of energy-related CO_2 emissions – see below). Over 80 percent of this carbon is captured from IGCC plants, and in hydrogen and synthetic fuel production, with technologies that capture carbon from post-combustion flue gases remaining relatively unattractive despite the climate change mitigation policies assumed under this baseline scenario.

2.2.2. Technology costs

The technological development of the energy system described above is driven by a number of factors, including among others the GHG tax, resource availability potentials, and absolute and relative market penetration constraints. However, two of the most important factors affecting technology choice are the cost and performance of competing technologies.

These in turn are affected by technology learning – both learning-by-searching and learning-by-doing – which are determined by the R&D budget allocation (see Section D1a(iii) [of the SAPIENTIA final report]), and experience with the manufacture, installation and operation of technologies. Table 2-2 presents the development of capital costs of some key learning technologies under this baseline scenario based on costs and learning parameters from Kouvaritakis and Panos (2005). However, as mentioned above, it is important to appreciate that technology cost and performance are only two of a number of factors that affect technology adoption.

The importance of other factors is illustrated when we look at the cost of nuclear generation in Table 2-2. This technology remains relatively expensive compared to other forms of generation, yet plays a major role in the electricity market at the end of the century because of depletion of gas resources, and the impact of the GHG tax on the competitiveness of coal-fired generation. This is also the case with most renewables, with the share of wind turbines limited by the availability of suitable sites.

Clearly, by the end of the 21st century fuel cells are the cheapest form of electricity generation capacity. However, the challenges associated with mobilising resources for hydrogen production, and developing the necessary distribution infrastructure constrain the penetration of this technology (as seen in Figure 2-1). This highlights that in order to fully exploit the potential of fuel cell technologies, there may be a need to develop a long-term strategy for development and investment to co-ordinate hydrogen production, distribution and utilisation. Table 2-2 shows, however, that the extensive experience with and R&D investment in stationary fuel cell electricity generation technologies is unable to bring down the cost of fuel cells sufficiently to make them

Table 2-2: Impact of technology learning on capital costs, baseline scenario (with GHG abatement policy)

Group	Technology	Abbreviation	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
			€99/kW										
Electricity generation technologies	Conventional Coal	HCC	1,219	1,214	1,161	1,121	1,077	1,045	1,018	995	974	958	947
	Integrated Coal Gasification Combined Cycle (IGCC)	HCA	1,436	1,375	1,335	1,293	1,254	1,209	1,172	1,166	1,159	1,153	1,148
	Oil Conventional Thermal	OLC	1,108	1,070	1,056	1,055	1,054	1,054	1,053	1,053	1,053	1,053	1,053
	Gas Turbine Combined Cycle	GCC	548	535	524	517	512	510	508	507	507	507	507
	Gas Conventional Thermal	GSC	986	942	920	902	892	888	884	884	884	884	884
	Gas Turbine Open Cycle	GTR	384	374	357	345	337	331	327	326	325	324	324
	Gas Fuel Cell (generic stationary)	GFC	11,755	5,806	2,870	1,053	691	477	336	265	234	206	186
	Nuclear (2nd and 3d gen.)	NUC	2,765	2,542	2,161	1,934	1,824	1,785	1,756	1,745	1,737	1,729	1,722
	New Nuclear (4th gen.)	NNU	8,555	7,406	6,525	5,689	4,395	3,406	2,655	2,276	1,959	1,684	1,454
	Biomass	BIP	2,477	2,081	2,006	1,954	1,907	1,868	1,836	1,836	1,836	1,836	1,836
	Large Hydro	HYD	3,227	3,144	3,064	2,931	2,747	2,524	2,381	2,311	2,286	2,270	2,250
	Solar Thermal Power Plant Cylindro-Parabolic	STH	3,111	2,889	2,674	2,465	2,280	2,130	2,006	1,999	1,991	1,985	1,983
	Building Integrated PV	SPV	6,385	4,622	3,748	3,033	2,523	2,021	1,796	1,751	1,749	1,748	1,743
	Wind Turbines	WND	1,061	957	880	813	767	737	716	713	710	709	708
	Hydrogen Fuel Cell (generic stationary)	HEF	11,755	5,806	2,870	1,053	691	477	336	265	234	206	186
			€99/m3d										
Hydrogen production technologies	Hydrogen from Gas Steam Reforming (large scale)	GASH2NE	46	45	36	36	36	36	36	36	35	35	35
	Hydrogen from Coal Partial Oxidation	COALH2NE	117	109	104	98	92	87	82	81	80	78	78
	Hydrogen from Biomass Pyrolysis	BIOH2NE	122	114	104	98	93	89	86	84	82	80	79
			€99/vehicle										
Passenger car technologies	Conventional ICE Passenger Car	ICC/ICG/ICA	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000
	Hybrid Passenger Car	ICH/IGH/IAH	7,700	5,834	5,402	5,102	5,004	4,956	4,918	4,900	4,888	4,879	4,873
	Hydrogen ICE-Hybrid Passenger Car	IHH	11,000	9,134	8,702	8,402	8,304	8,256	7,593	7,552	7,531	7,518	7,509
	Reformer-Fuel Cell Passenger Car	PFC/AFC	590,200	352,259	234,802	162,135	147,645	139,063	133,432	130,602	129,351	128,254	127,449
	Hydrogen Fuel Cell Passenger Car	HFC	472,600	234,659	117,202	44,535	30,045	21,463	15,378	12,531	11,274	10,173	9,366
			€99/toe input pa										
Carbon capture technologies	Pre-Combustion CO_2 capture (IGCC)	HCACS	31	10	10	10	10	10	10	10	10	10	10
	Post-Combustion CO_2 capture (Conventional Coal)	HCCCS	52	26	23	22	20	20	20	20	20	20	20
	Post-Combustion CO_2 capture (GCC)	GCCCS	31	24	13	13	13	13	13	13	13	13	13
			€99/m3d										
	Pre-Combustion CO_2 capture (Hydrogen Production)	H2CAS	68	68	45	45	45	45	45	45	45	45	45

attractive in the private automobile market. This explains the technology mix for the transport sector presented in Figure 2-3, after accounting for resource constraints that promote the adoption of the more-expensive hybrid electric vehicles.

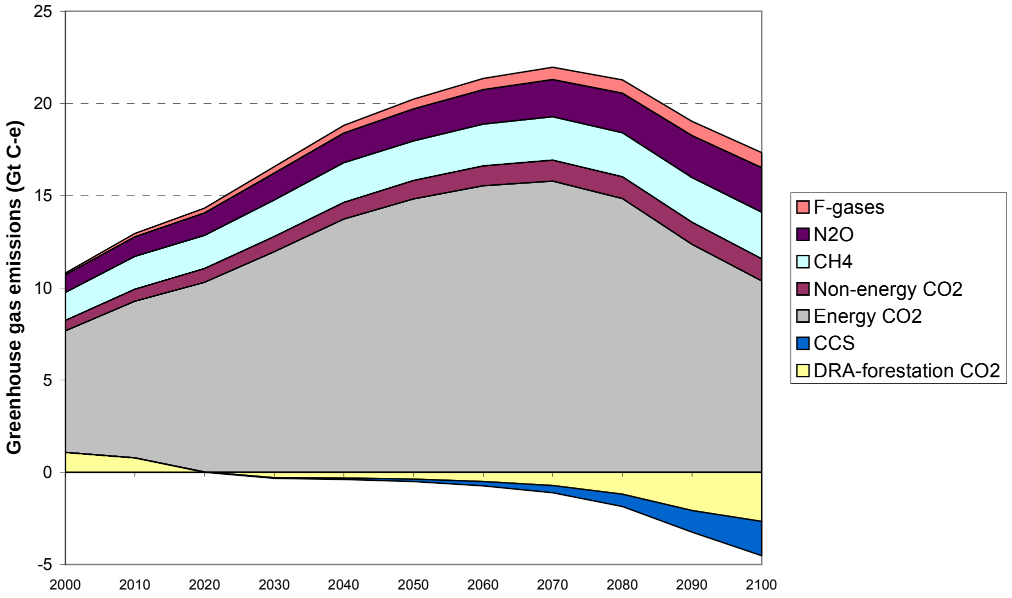
Of the other technologies presented in Table 2-2, the cheapest hydrogen production technology is not utilised because of competing demands for limited natural gas resources, whereas for carbon capture technologies, the investment cost per unit of energy processed is not the most important factor – instead, the cost of capture per tonne of carbon and whether the base electricity or hydrogen production technology is attractive are of more importance. This explains why the carbon capture technologies adopted are not necessarily the cheapest.

Now that we have a sense of technology development, and the forces affecting technology choice and the evolution of the global energy system under the baseline scenario, we can now return to the main focus of this analysis – to investigate how technology costs and rates of adoption are affected by technology support policies, including R&D and D&D, and the extent to which these policies can ultimately improve indicators of sustainability. Accordingly, below we examine the level of key indicators of climate change and security of energy supply under this baseline scenario, which establishes the benchmark against which the impact of R&D and D&D policies can be evaluated.

2.2.3. Indicators of sustainability

Greenhouse gas emissions represent an important link in the causal chain between policy instruments and climate change impacts, because the impact of any policy initiative on climate change indicators operates via its impact on emissions. Accordingly, we present in Figure 4 below the levels of global emissions and sequestration of different greenhouse gases under the baseline scenario. In this scenario, global net greenhouse gas emissions continue rising until around 2070 where they peak at almost 22 Gt carbon equivalent per annum. Apart from a shift to less carbon-intensive energy sources one of the main sources of abatement comes from sequestration – both geological and terrestrial.

Figure 2-4: Global greenhouse gas emissions, baseline scenario (with GHG abatement policy)



Note: Carbon capture and storage (CCS) from energy emissions is also indicated, as are net emissions or sequestration from deforestation, reforestation and afforestration (DRA-forestation).

The impact of this emissions trajectory on atmospheric concentrations of CO_2 and CH_4 is presented in Figure 2-5, based on output from the MAGICC climate model (Wigley and Raper 1997). Figure 2-5 also shows the uncertainty range for future CO_2 concentrations described by high and low estimates for climate sensitivity. Under this scenario, atmospheric concentrations of carbon dioxide increase from around 350 ppmv in 2000 to around 700 ppmv in 2100. The impact of the change in atmospheric concentrations of CO_2, CH_4 and other gases on global temperature and sea-level is illustrated in Figure 2-6. Under the middle estimate of climate sensitivity (2.6 K per doubling of CO_2 concentration), average global temperature increases to around 3.2 K above 1990 levels by the end of the century, while the average rise in sea level is more than 400 mm. In Figure 2-6 we again present the uncertainty range for future global temperature change implied by the high and low estimates of climate sensitivity. The extent of the uncertainty associated with this indicator needs to be considered when interpreting results in the remainder of this analysis, where we seek to explore whether technology support policies, including R&D and D&D can help to mitigate some of these effects of climate change.

Figure 2-5: Atmospheric concentrations of carbon dioxide and methane, baseline scenario (with GHG abatement policy)

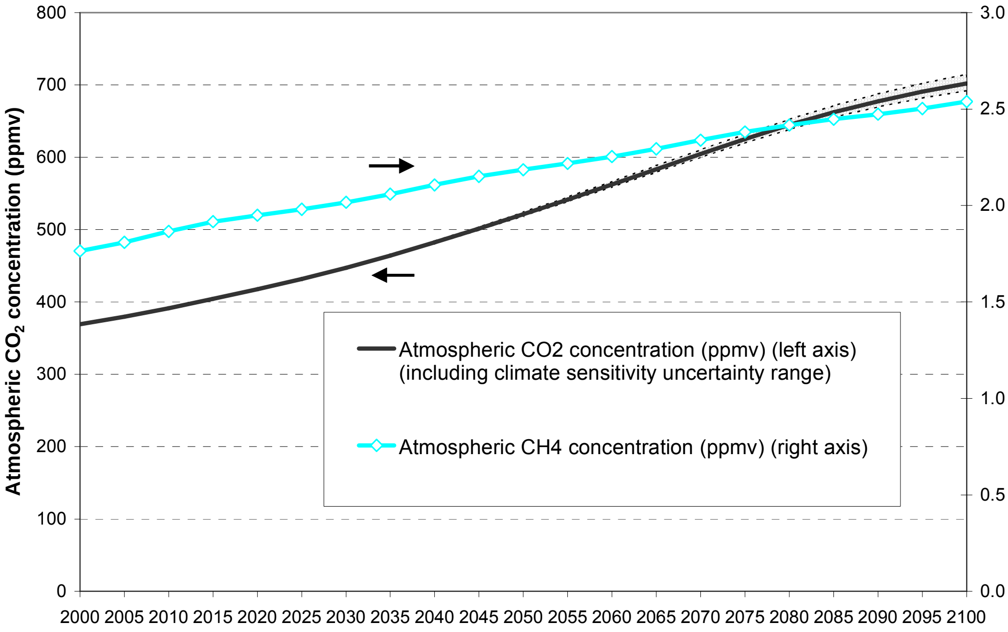
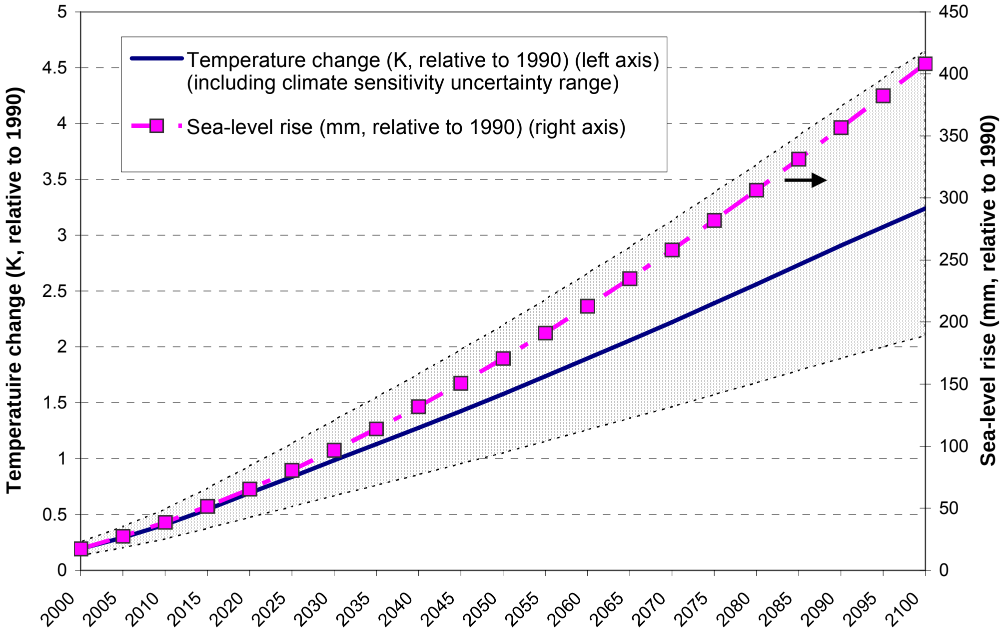
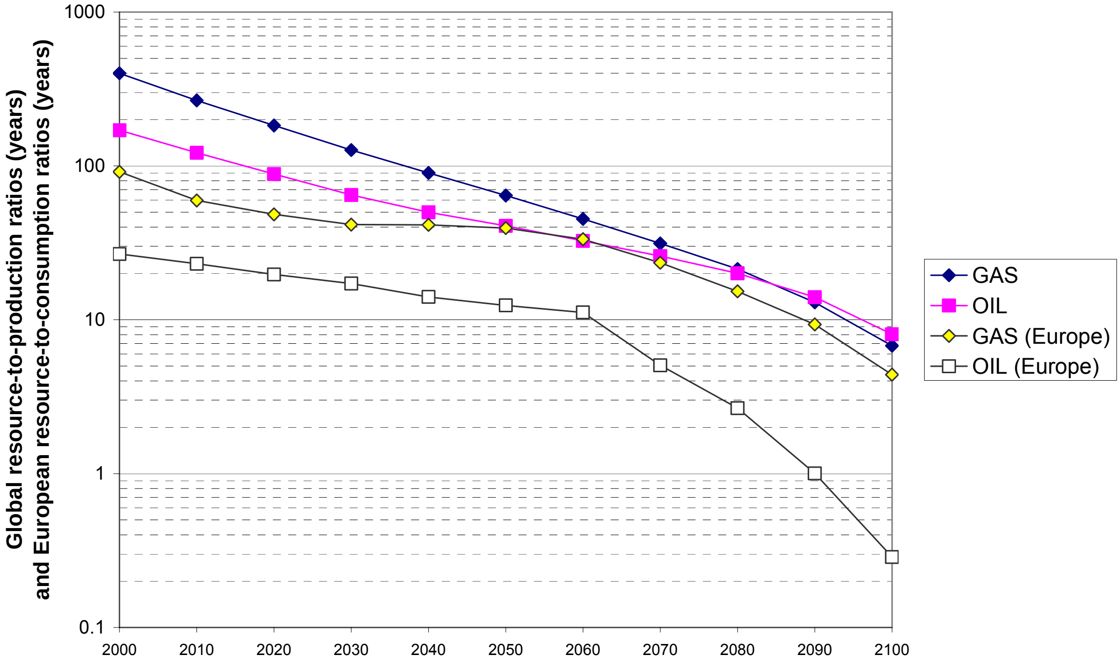


Figure 2-6: Temperature change and sea-level rise, baseline scenario (with GHG abatement policy)



The other major element of long-term sustainability examined in this report is the need to maintain security of energy supply, which may be particularly challenging for oil and gas resources. As an indicator of global resource security and availability, the development of the global resources-to-production ratios for oil and gas are presented in the following figure. Importantly, this indicator differs from the reserves-to-production ratio

Figure 2-7: Global oil and gas resource-to-production ratios and European resource-to-consumption ratios, baseline scenario (with GHG abatement policy)



used to measure short-term oil security, since it seeks to incorporate all resources (not only identified reserves). Resources estimates are from Rogner (1997) and fixed for the analysis, so the R:P ratio changes only because of changes in consumption, whereas reserves will change with new discoveries (of existing resources) and improvements in extraction technologies. Since the focus of this analysis is on the long term, we are more concerned with sustainability of the resource base, rather than the efficiency with which resources can be reclassified to reserves.

Figure 2-7 also presents the resource-to-consumption ratios for Europe (comprising all of Europe up to the borders of the former Soviet Union), to provide an indication of potential oil and gas self-sufficiency in this world region – or the potential susceptibility to a long-term disruption to international fuel trade.

Having described they key elements of the baseline scenario, and the baseline indicators of climate change and security of energy supply, we can now turn to the impact of alternative technology policies on these indicators.

3. Outlook Using the GMM Model

In order to give an adequate context to our analysis, in this section we describe the main characteristics of our baseline scenario, as quantified with the GMM-MAGICC modeling framework. Technology assumptions in this scenario have been made consistent with the technology description of the TechsDB database developed for SAPIENTIA.

The baseline scenario used for SAPIENTIA includes a climate policy in all regions, which was defined using a Delphi method among the project participants. This policy is incorporated as an implicit time-dependent CO_2 tax in all regions. In this scenario, the EU leads the world climate abatement followed by lesser efforts in other industrialized regions. Developing regions undertake abatement efforts only after industrialized regions do and their efforts are smaller than those in industrialized regions (see Kouvaritakis, 2005a). The baseline scenario presented here has been constructed using the common assumptions within the SAPIENTIA project regarding the outlook for R&D effort directed to different technological options (see Kouvaritakis, 2005b).

Figure 3-1 presents the world primary energy consumption in the baseline scenario. By the year 2050, primary energy consumption reaches about 950 EJ, i.e. it more than doubles as compared to year-2000 levels. Although non-fossil energy resources increase their contribution significantly, fossil fuels still dominate the primary energy mix during the first half of the 21st century. Specifically, the use of natural gas, the less carbon-intensive fossil fuel, experiences a significant increase. Coal consumption also grows in absolute terms but to a lower extent while oil consumption grows only slightly. The growth of coal consumption is basically driven by the use of coal for electricity generation as will be seen below. Nuclear energy experiences a revival and its contribution grows significantly. Renewable energy use also expands dynamically during the 2000-2050 period.

Figure 3-1 World primary energy consumption in the baseline scenario between the years 2000 and 2050. The primary energy for the nuclear and other renewables categories has been computed using the fossil equivalence method.

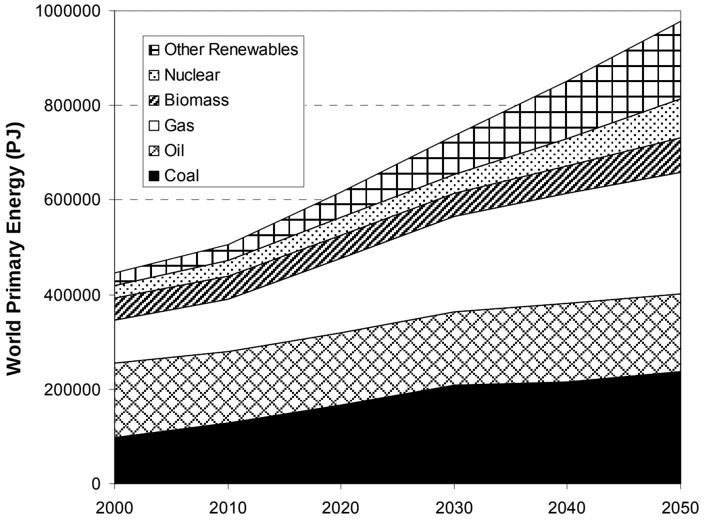


Figure 3-2 presents the global electricity generation mix by fuel in the baseline scenario. Electricity generation increases substantially, reaching more than four (4) times its levels in the year 2000. As mentioned before, in this scenario coal-based power plants still experience a substantial absolute growth but after the year 2030 the growth occurs at a substantially slower rate. Moreover, in the remaining coal-based fraction of the electricity mix, a gradual transition occurs from conventional coal-fired plants towards more efficient and clean Integrated Gasification Combined Cycle (IGCC) plants. The contribution of natural gas increases substantially mainly driven by the growth of highly efficient combined-cycle gas turbines and natural gas becomes the second most important primary fuel in the global electricity sector by the year 2050, despite being actively sought after in other energy sectors. Nuclear power plants also experience a substantial increase along this 50-year period with improved conventional nuclear designs (inherently safe and more efficient new reactor designs of the generations III and III+). There is, however, no penetration of advanced, generation IV nuclear power systems. Renewable sources including hydro power plants exhibit a dynamically growing contribution to the generation mix. Specifically, among the new renewable sources, wind turbines and, to a lower extent, biomass-based power plants make sizeable inroads into the system. In the latter case, combustion-based facilities are gradually replaced by more efficient and flexible biomass gasification systems.

Figure 3-2: World electricity generation by fuel in the baseline scenario between the years 2000 and 2050.

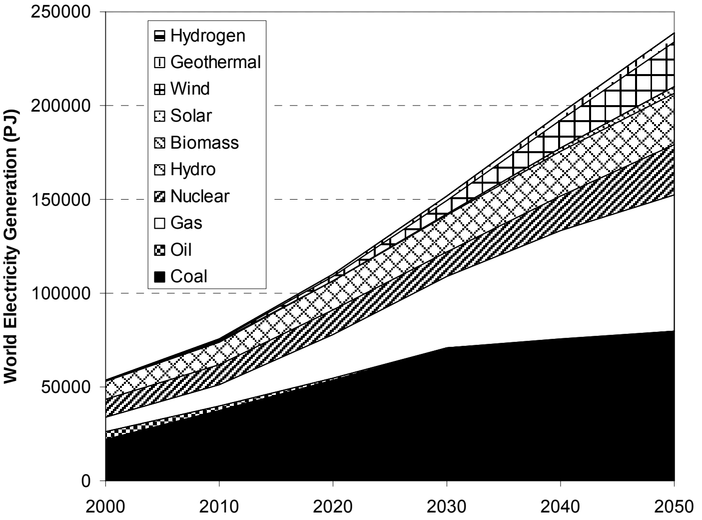


Figure 3-3 depicts the technology mix in the global passenger car sector, where an incipient technology transition can be observed. While conventional internal combustion engines (ICE) based on oil products still dominate the passenger car mix to a large extent during a large part of first half of the 21st century, they gradually decline their market participation towards the year 2050. Advanced ICE vehicles and hybrid-electric vehicles (HEV) gradually, but steadily, gain market share. Specifically, natural gas-powered and oil-product-based HEVs experience a dynamic growth, accounting together for about 20% of passenger car mobility in the year 2050. Electric vehicles (EV) occupy a niche market while fuel-cell hybrid vehicles (FCV) remain "locked-out" and do not penetrate the market during this time period.

Figure 3-3: World use of passenger cars (in billion vehicle-km traveled) for the baseline scenario between the years 2000 and 2050. The abbreviations are as follows. ICEV stands for Internal Combustion Engine Vehicles, HEV stands for Hybrid-Electric Vehicles and FCV stands for Fuel-cell-hybrid vehicles.

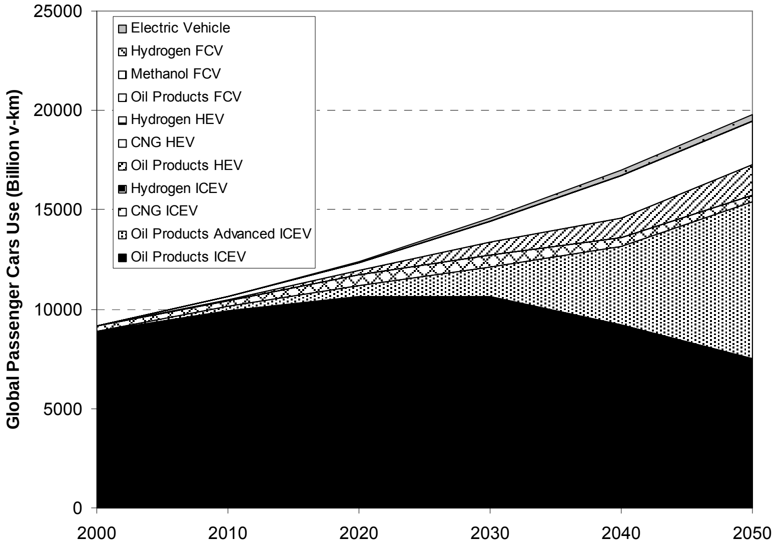
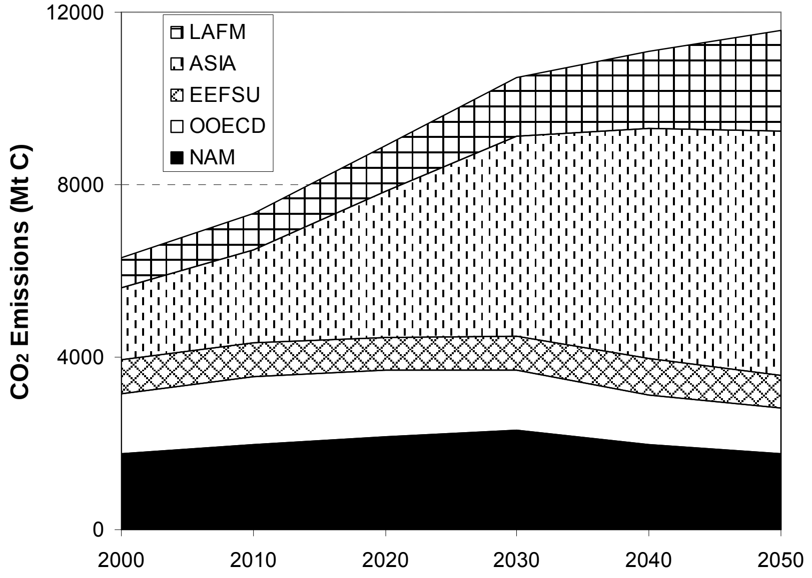


Figure 3-4 presents the global CO_2 emissions in the baseline scenario by region. Under the influence of increasingly stringent climate-change policies around the world, CO_2 emissions still grow but gradually diminish their growth rate. By the middle of the 21st century, CO_2 emissions are approximately 11.5 Gigatons of carbon (GtC), which represents a more than 80% increase relative to the levels of the year 2000. The bulk of emissions growth comes from developing regions and, specifically, developing ASIA. CO_2 emissions in currently industrialized regions, where the most stringent carbon price signals are imposed, decline in the long term.

Figure 3-4: Global CO_2 emissions by region in the baseline scenario. The regional abbreviations are as follows: North America (NAM), Rest of the OECD in the year 1990 (OOECD), Former Soviet Union and Eastern Europe (EEFSU), developing Asia (ASIA, without Japan) and the rest of the world (Latin America, Africa and the Middle East, LAFM).



The carbon-equivalent (C-eq) emissions of the three greenhouse gases (GHG) included in this analysis (CO_2, CH_4, N_2O) in the baseline scenario are shown in Figure 3-5. The aggregated emissions of these three GHG reach approximately 17 Gton of C-eq in the year 2050. As expected, CO_2 emissions represent the largest fraction, followed by CH_4 and N_2O, respectively. In computing these emissions, 100-year global warming potentials (GWP) as specified by IPCC (2001) have been used, namely 21 for CH_4 and 310 for N_2O. Notice that only energy-related CO_2 emissions are considered here. The cumulative CO_2 emissions for the period 2000-2050 in the baseline scenario are 557 Gt C. The cumulative CH_4 emissions for the period 2000-2050 in the baseline scenario are 188 Gt C-eq.

Figure 3-5: Carbon-equivalent emissions of the three greenhouse gases (CO_2, CH_4, N_2O) in the baseline scenario.

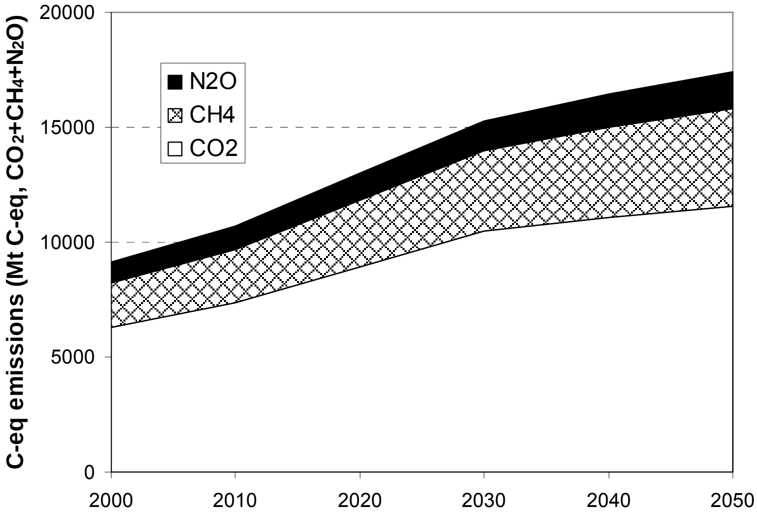


Figure 3-6 depicts the atmospheric concentrations of CO_2, CH_4 and N_2O for the period 2000 to 2100 as computed with the MAGICC climate model (Wigley and Raper, 1997; Hulme *et al.*, 2000; Wigley, 2003).[19] Historical values up to the year 1990 are shown for reference purposes. The time horizon of the energy-system GMM model is only up to the year 2050. Thus, GHG emissions and the corresponding atmospheric concentrations correspond to the model output for the period 2000 to 2050. For the period 2050-2100, GHG atmospheric concentrations were estimated assuming that GHG emissions remain constant at their levels of the year 2050. Therefore, the concentrations for this period correspond to the "commitment" that the atmospheric system would undergo if no further increase (or decrease) in emissions would take place.

In the baseline scenario, the atmospheric concentration of CO_2 reaches approximately 479 parts per million in volume (ppmv) in the year 2050 and the "commitment" is 600 ppmv by the year 2100. The CH_4 concentration in the year 2050 is about 3200 parts per billion in volume (ppbv) and the "commitment" for the year 2100 is 3740 ppbv. As for N_2O, its atmospheric concentration increases much slower to 373 ppbv in the year 2050 and a "commitment" of 429 ppbv for the year 2100.

---

[19] The runs with the climate model MAGICC have been conducted using a climate sensitivity of 2.6 °C, a net CO_2 fertilization effect of 1.1 GtC/year and aerosol radiative forcing of -0.4 W/m^2 (direct),-0.8 W/m^2 (indirect) and -0.2 W/m^2 (biospheric) respectively. The MAGICC climate model requires emission pathways for other greenhouse gases, which are not computed by the GMM model. In this case, they have been taken from the IPCC/SRES B2 scenario as quantified with the MESSAGE and AIM models (SRES, 2000).

Figure 3-6: Atmospheric concentration of three greenhouse gases (CO_2, CH_4 and N_2O) in the baseline scenario. Notice that concentrations after the year 2050 are computed assuming that emissions remain at the levels of the year 2050. That is, they correspond to a so-called "commitment".

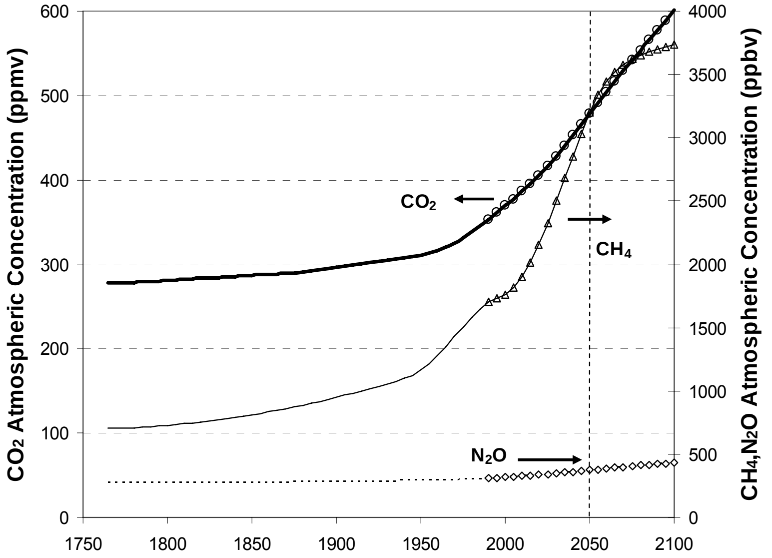


Figure 3-7 presents the global annual-average temperature change and global average sea-level rise relative to the year 1990 in the baseline scenario. As with the GHG concentrations above, values after the year 2050 are estimated on the assumption that the GHG emissions remain constant at 2050-levels. That is, they correspond to temperature and sea-level rise "commitments". Under this scenario, global temperature change from the year 1990 reaches about 1.5°C in 2050 and a "commitment" of approximately 1.9 °C for the year 2065 (15-year commitment after 2050) and 2.7°C for the year 2100, respectively. As for sea-level rise, it reaches 16.5 cm in 2050 and a "commitment" of about 37 cm for the year 2100. It must be emphasized that huge uncertainties surround these figures, related to the climate sensitivity, radiative forcing of aerosols and fertilization effects of CO_2, among others.

Figure 3-7: Global annual-average temperature change and global average sea-level rise relative to the year 1990 in the baseline scenario. Values after the year 2050 are estimated on the assumption that the GHG emissions remain constant at 2050-levels. That is, they correspond to temperature and sea-level rise "commitments".

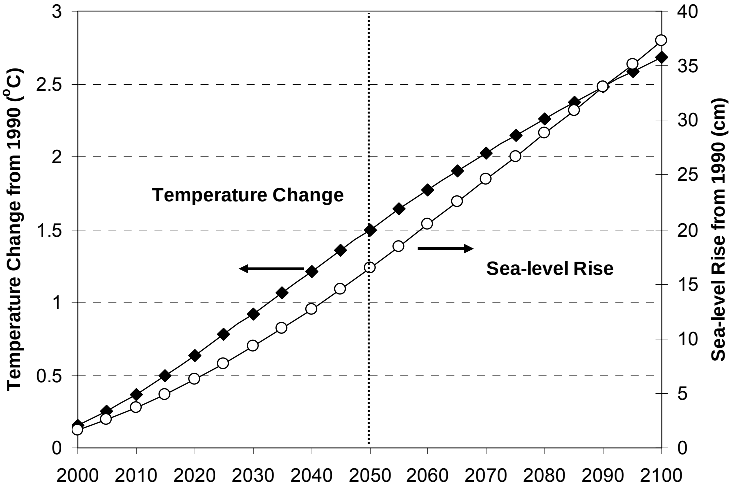


Figure 3-8 presents the global temperature increase per decade in the baseline scenario. Values after the year 2050 have been estimated assuming that GHG emissions remain constant after 2050. The decadal rate of variation of temperature increases over the 2000-2050 period and decreases afterwards, always remaining above the "safe" value of 0.20°/decade discussed in the literature. The highest temperature increase over a decade for the period 2000-2050 is of 0.29°C/decade and occurs between the years 2040 and 2050. The reader should bear in mind that the calculations after the year 2050 assume that GHG emissions remain constant at the 2050-levels.

Figure 3-8: Global temperature increase per decade for the baseline scenario. Values after the year 2050 have been estimated assuming that GHG emissions remain constant after 2050.

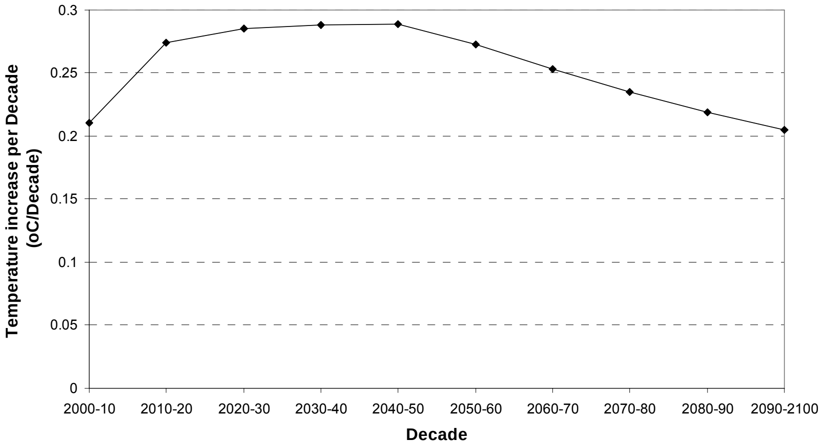
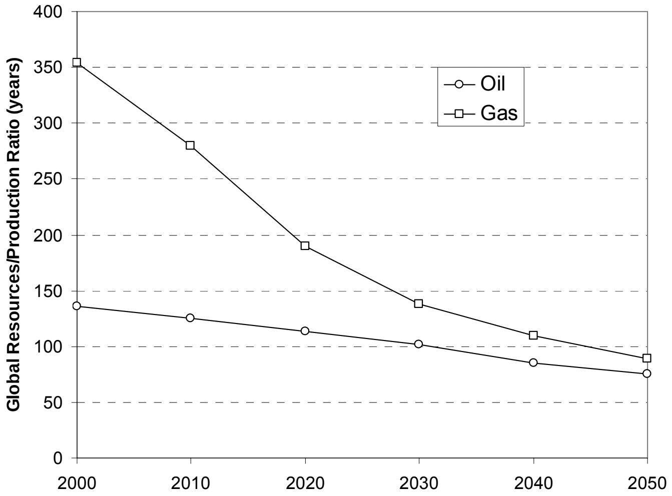


Figure 3-9 shows the resource-to-production (Ru/P) ratios for oil and natural gas resources in the year 2050 for the world as a whole. The Ru/P ratios for the year 2050 represent the amount of years that a given region could sustain its consumption of oil and natural gas respectively, were it to stabilize at the levels of the year 2050. The resource base used to compute the Ru/P indicator includes both conventional and unconventional resource categories specified in the GMM model for this scenario, which correspond to categories I to V for oil and I to VI for gas in the resource characterization presented by Rogner (1997,2000), as described in Barreto and Kypreos (2004b). That is, the Ru/P indicator differs from the commonly used reserves-to-production ratio (e.g., BP, 2004). As can be seen, by the middle of the 21st century, at the global level the oil Ru/P ratio achieves 75 years while the natural gas Ru/P ratio is approximately 89 years. Notice that there is uncertainty surrounding the amount of non-conventional oil and gas resources and the feasibility of their exploitation (e.g. The Economist, 2005).

Figure 3-9: World resources-to-production ratios for oil and natural gas in the baseline scenario. The resource base used to compute the Ru/P indicator includes both conventional and unconventional resources specified in the GMM model.



The fraction of oil production that originates in the LAFM region, comprising Latin America, Africa and the Middle East and where politically-volatile countries are in possession of substantial oil resources, in the baseline scenario is 58% for the year 2050.

4. Outlook Using the MARKAL Model

4.1. Baseline assumptions

Starting point is the exiting Western European database with its underlying assumptions, particularly on fuel prices, technology and resource availability, and technical and economical parameterisation such as technology discount rates (hurdle rates a proxy for investors' behaviour). The underlying macro-economic background (and hence the basis for the exogenous determined end use demand lev-els) is a scenario with a moderate but steady growth (2.4% -> 1.9% GDP growth/annum over 1990-2050), with increasing but still moderate fossil fuel prices and with no foreseen depletion of fossil fuel stocks and supply. The overall discount rate used is 4%, in line with the Commission's request for the SAPIENT project. The model database contains data up to 2100, but for this project scenarios will be run to 2070. Results will be reported to 2050 only, first of all because POLES, PROMETHEUS and ISPA do not have a longer time frame, secondly end of period effects will be avoided since the model will run two decades further.

From the survey and Delphi study performed by NTUA for this project, the following assumptions guided the approach to include climate policy into the model run:

- Western Europe will continue to lead the world's climate change abatement effort;
- for the models, the measure to represent the climate policy effort will be the application of a carbon (CO_2) value rather than a GHG or CO_2 emission target;
- there is no feedback form the climate change process (or the resulting emission levels) to the level of the CO_2 tax.

From the survey the likely CO_2 taxes for Europe were determined. In addition to the mean value, also a maximum value (see Criqui P., Athens Oct 2004) was introduced as separate case. This lead to the following agreed CO_2 taxes to be included in the CO_2 policy runs:

Table 4-1: CO_2 taxes included in the policy runs

		2005-2010	2011-2020	2021-2030	2031-2040	2041-2050	2051-2100
€/ton CO_2	CO2POL1 case	11	17	28	45	61	85
	CO2POLH case	33	51	76	119	158	216

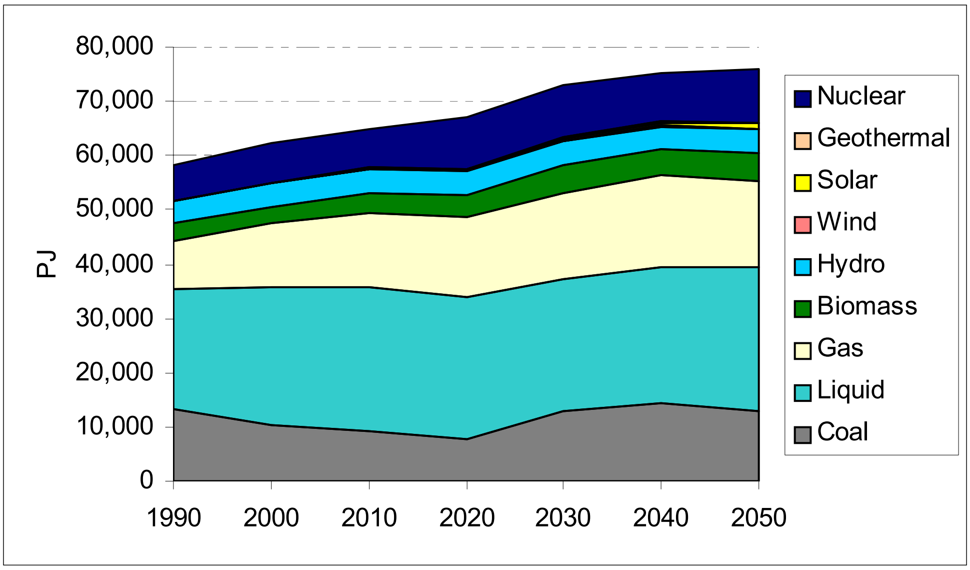
4.2. Baseline results

For the base case, i.e. the case without CO_2 taxes against which the results of further policies are to be gauged, a number of representative results are reported below in the next paragraphs. The results give an indication of development of the indicators as determined in Work Package 2 of the SAPIENTIA project. The indicators that will be illustrated are: primary energy use and import dependency; CO_2 emissions and CO_2 capture and storage; the (marginal) costs for gas and oil and electricity.

4.2.1. Primary energy mix and import dependency

The primary energy mix shows a conservative view on the future energy development: fossil energy carriers, and mainly oil, continue to dominate the mix to 2050 and beyond. The modest increasing fuel prices and the absence of disturbances in supply lay mainly at the origin of this. The consumption increases with about 0.4% per year between 1990 and 2050. The share of renewables in the primary mix remains more or less constant at about 20%, to a large extend due to the inclusion of Norway in the WEU[20] region. Also nuclear retains it share, as neither an explicit phase out of nuclear power plants, nor a forced introduction of new nuclear capacity is included in the scenario.

Figure 4-1: Primary energy [PJ] in the reference case



To express security of supply, several indicators are use and referred to. The most common one is import dependency. However in line with a more extended view on security of supply, in this report the complement of import dependency will be used, namely the import independency. The rationale is that the other indicators used represent situation where the higher the value is the more favourable the energy security situation can be regarded to be.

---

[20] Norway has a very large contribution (almost 100%) from renewables (hydro) in the power production sector.

The import independency can be expressed as the amount of domestic supply over the total energy sup-ply (index 0). This gives indeed an indication on the import independency, but not on critical supplies. From the table it is clear that domestic supply decreases continuously and hence imports will play an increasing role in the Western European fuel supply. By 2030, hardly 30% of the supply is domestic, almost all coal and oil are imported.

Table 4-2: Import independency (total domestic supply/total primary energy)

	1990	2000	2010	2020	2030	2040	2050
index 0	58.80%	59.10%	47.00%	34.10%	30.00%	29.20%	28.70%

A series of indices named after Shannon shed a more detailed light on the distribution of the energy mix, over the import mix over the different energy carriers and over the regions of origin. Since the MARKAL model used does not comprise other world regions, nor consider distinct flows from world regions, assumptions for the latter dependency had to be added.

The first index weighs the primary energy portfolio across the different energy carriers included in the analysis. This gives a representation of the balance within the primary mix, indeed the more equal the shares of the different energy carriers, the higher the index and the better the region's ability to diversify its supply.

$$\text{index1} = -\Sigma(p_i \times \ln p_i) \qquad (1)$$

with p_i the share of the energy carrier (i) in the primary mix.

With 9 energy carriers, the maximum obtainable value is 2.197 (S_{max}). The lower the calculated value is compared to this value, the less equally distributed the fuel supply is, i.e. there is one or more dominating fuels. In Western Europe, 2 of them, coal and oil are together already responsible for 50% of the supply, resulting in an index that is only 70 - 75% of the maximum value.

The second index extends on the first by adding an adjustment for the import share of each energy carrier, introducing a coefficient c_i to equation (1). The coefficient c_i is a function of the import share m_i of energy carrier (i).

$$ci = 1- mi \times [1+(mi/\ln mi)/Smax] \qquad (2)$$

$$\text{index2} = -\Sigma\ (ci \times pi \times \ln pi) \qquad (3)$$

Not all energy carriers have an import (e.g. hydro, wind, …), there share m_i is 0 and c_i is 1. When an energy carrier is completely imported, m_i is 1 and c_i is zero, thus reducing the value of the index2 (equation (3)). As oil becomes almost completely imported, its contribution to the index is very small and responsible for the bulk of reduction between index1 and index2.

The last index takes into account the stability of the region of origin of the import. As the model does not include other world regions and thus possible supply regions For Western Europe, the index has been calculated using the following stability index hi for the import (0 is highly instable, 1 is very stable):

coal	0.8
oil	0.5
gas	0.5
biomass	0.8
nuclear (Uranium)	0.5

The stability factor is incorporated as the coefficient c'_i, according to:

$$c'_i = 1- m_i \times [1+(h_i \times m_i/\ln m_i)/S_{max}] \qquad (4)$$

$$\text{index3} = -\Sigma\ (c'_i \times p_i \times \ln p_i) \qquad (5)$$

Since oil is already completely imported, the origin of the supply does not alter the value of the index much, only the other imported fuels reduce the index value further. Nevertheless the reduction between index 2 and index 3 is quite small.

The resulting values for the indices are given below, relative to the maximum. The lower the value, the less favorable the situation is.

Table 4-3: Shannon indices reference case

	1990	2000	2010	2020	2030	2040	2050
index1	72.7%	71.8%	72.2%	73.5%	76.6%	76.2%	77.0%
index2	47.5%	45.2%	39.2%	36.0%	33.2%	32.6%	33.2%
index3	47.5%	45.2%	37.7%	34.6%	31.9%	31.3%	32.0%

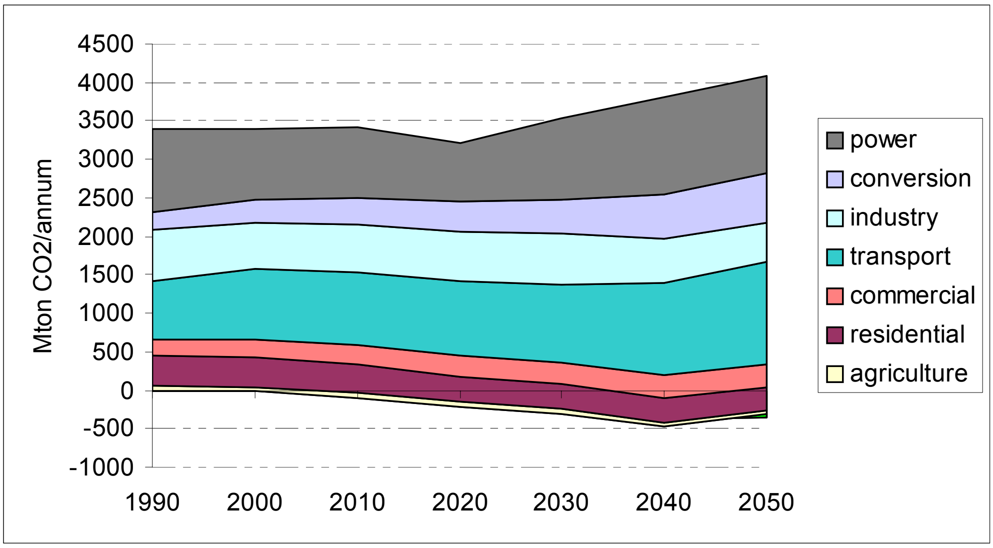
Looking at these indicators, the conclusion can be made that Western Europe, although having a well spread primary energy supply mix, is very much dependent on import (mainly coal and oil). This situation worsens over time and makes the region a potential victim of international market disturbances.

4.2.2. CO_2 emissions

The primary mix as illustrated in the previous paragraph shows a large contribution from fossil fuels. These fuels lead to CO_2 emissions from combustion. Although the model also can account for CO_2 emissions from specific industrial processes (amongst others those from iron and steel or cement pro-duction) these are not included in the reported CO_2 emissions. As part of emission bookkeeping, the model also includes description of possibilities to store emissions in geological formation (sequestration or CCS) as well as in biological options (forests, soil) (sinks).

In the next figure, CO_2 emissions show a clear increasing trend, with a slight dip around 2020 mainly caused by the fuel consumption mix changes in the power sector (switch to gas). The main sectors re-garding emissions are the power sector and transport. Furthermore, emissions fall below the zero axis due to sinks and CCS. Sinks take up CO_2 from the atmosphere whereas CCS stored CO_2 orginating from specific capture processes at industrial or power plants. The CCS mainly occurs in the power sec-tor, but also in industry there is some capture and storage of CO_2 (50 Mton/year) (see also later).

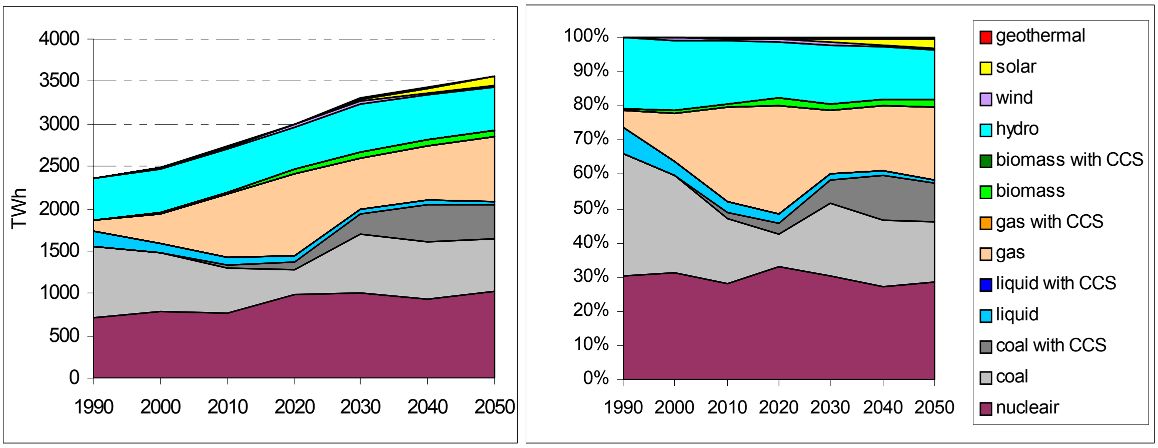
Figure 4-2: Gross sectoral CO_2 emissions reference case [Mton/year]



4.2.3. Power production

Since the large contribution of the power sector to the overall CO_2 emissions and to the amount captured, it is worthwhile to look into the power production, particularly as it is likely to show substantial effects from the policies considered in the non-base scenarios. From 2010 onwards, CCS from coal fuelled power plants appears, first modestly, but after 2030 more than 1/3 of all coal fuelled production is equipped with CCS. The economic benefits arising from storing the CO_2 in unmineable coal seams with methane recuperation drive the deployment of CCS.

Figure 4-3: Electricity production [in TWh and %] in the reference case



Nuclear maintains a share of about 30 % over the time horizon, whereas gas increase considerably in the early decades, but ends with about 20%, coal decreases first but regains some importance and ends at about 30%. All in all, the power mix remains quite diversified. The renewables are mainly realized by hydro power. Wind, solar and the others grow but remain small. The share of renewables remains fairly constant at 20%.

Table 4-4: Renewable share in electricity production

	1990	2000	2010	2020	2030	2040	2050
share renewables in the power mix	21.1%	21.9%	20.1%	19.5%	21.1%	19.8%	20.0%

The CO_2 content of the electricity produced decreases up to 2020 due to the decarbonisation of the fuels. This is realised through the use of zero emission fuels (nuclear, renewables), but more importantly through fuel switching (mainly coal to gas). Due to the revival of coal (even with CCS), CO_2 content increases after 2020 but remains more or less stable afterwards. CCS from coal turns coal into an al-most zero emission fuel, however 10% of the carbon in coal still is emitted.

Table 4-5: CO_2 intensity electricity [kg/kWh]

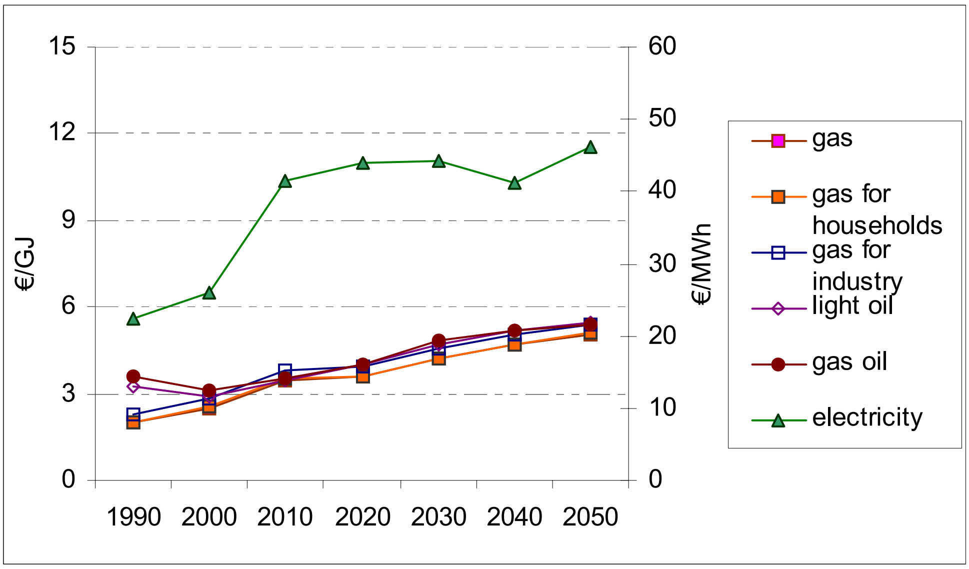
	1990	2000	2010	2020	2030	2040	2050
kg CO_2/kWh	0.454	0.373	0.324	0.226	0.259	0.265	0.264

4.2.4. Marginal fuel costs

As MARKAL is an optimization model, it uses and generates the dual solution value of fuel prices (the marginal cost) and not the primary values (fuel costs). For the rest of the analysis presented in this re-port, the marginal costs will be used. Marginal costs can be seen as the (imaginary) cost to sup-ply/consume one more unit of that fuel compared to the total amount of the scenario run solution. This can be compared to the derivative value in the solution point, but this notion is not used here further.

For this analysis, and in line with the guidance fro WP2 on indicators for the SAPIENTIA project, results on marginal fuel cost are reported for gas, oil and electricity. For gas, the costs are given for the (generic) gas supply mix (gas) and for two important end use sectors, namely industry and residential. These sectors are important in light of the extension of the number of key components and the corresponding technology coverage. For oil, light crude oil is taken as representation of the supply side and gas oil is representing the end use side. Electricity, although not explicitly mentioned in WP2.1 of SAPIENTIA, is nevertheless included seen the large importance of the power sector as energy con-sumer and emission source and as sector with a considerable amount of ETL technologies. The annual average cost is given, although the model distinguishes 6 seasonal load fractions. The costs of the sea-sonal electricity are combined into a annual average.

Figure 4-4: Marginal fuel costs



4.2.5. Technology spill-over

In order to analyse the technology spill-over effects of the enlarged technology database and cluster matrix, as well as to explore where the interesting areas are for the R&D shocks analysis, detailed results of those clusters that have technologies in different sectors are given. This illustrates the sectoral spill-over achieved in the MARKAL modelling effort for SAPIENTIA.

The clusters mentioned are:

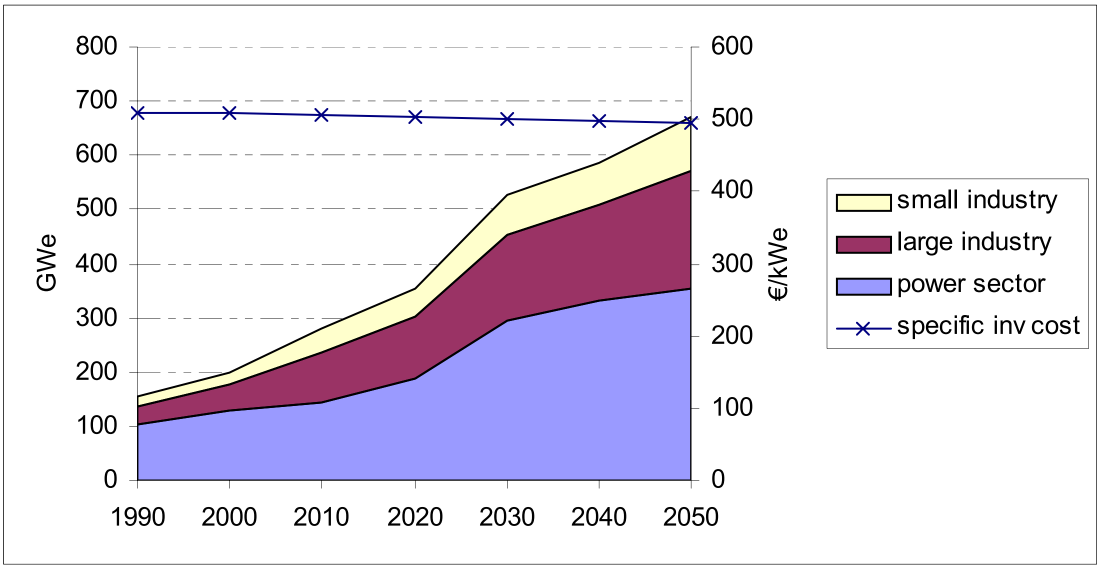
- boilers: industry and power sector
- gas engine: transport and power sector
- heat pumps: residential, commercial and industry
- CO_2 injection: industry and power sector

Also fuel cells and CO_2 capture from coal are candidates, but they do not appear as result technologies.

Boilers

Boilers are as said found in industry and in the power sector as part of the more "classical" types of power plants. Boilers are a typical example of a mature technology, having a low learning rate (high PR) and a large capacity history, resulting in few more cumulative capacity doubling and hence limited cost reductions. Nevertheless, boilers remain a widely used technology and the inclusion of industrial applications clearly contributes to the further deployment and development of boilers. In the model a further distinction between small and large industry is made. The resulting cumulative capacity over 1990-2050 and split by end use sector (large and small industry and the power sector) together with the evolution of the specific investment cost are illustrated below. The inclusion of industry causes a doubling of the cumulative capacity compared to a situation where boilers were only modelled as key component in the power sector.

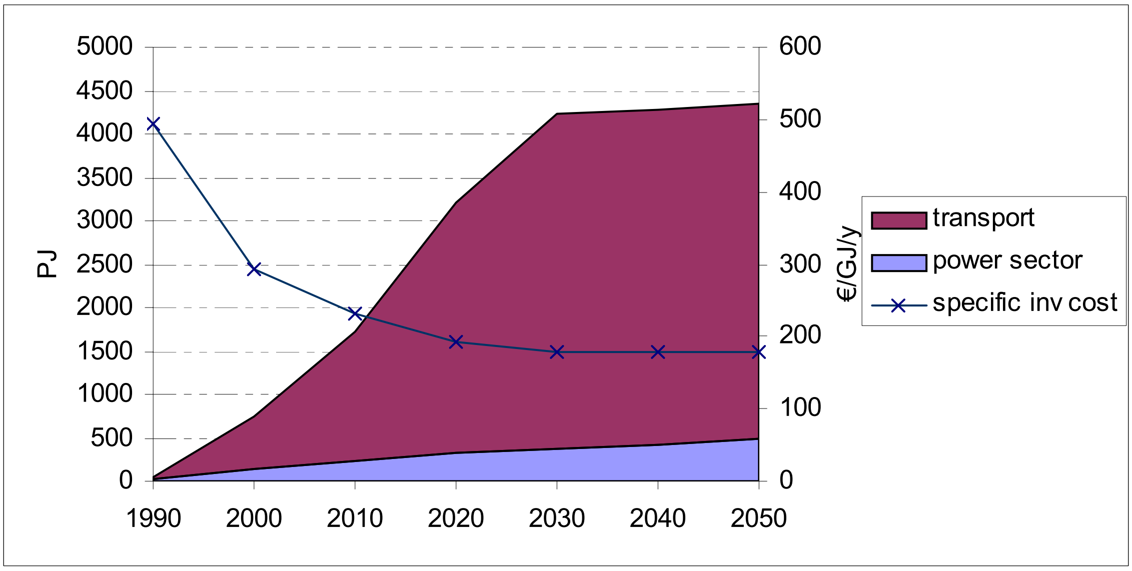
Figure 4-5: Boilers: cumulative capacity build up (GWe) and investment cost development (€/kWe)



Gas engines

Gas engines as key component are found in both mobile applications and in stationary applications. In the results, they appear only in advanced passenger cars and trucks in transport and in the stationary power application, they appear in the form of CHP gas engines delivering heat to the built environment. The latter application is quite small compared to the transport sector. Also it can be seen from Figure 4-6 that the application in the transport sector reaches a saturation level, caused by the appearance by 2030 of other mobile drive system options which satisfy the boundary conditions in a more cost efficient way.

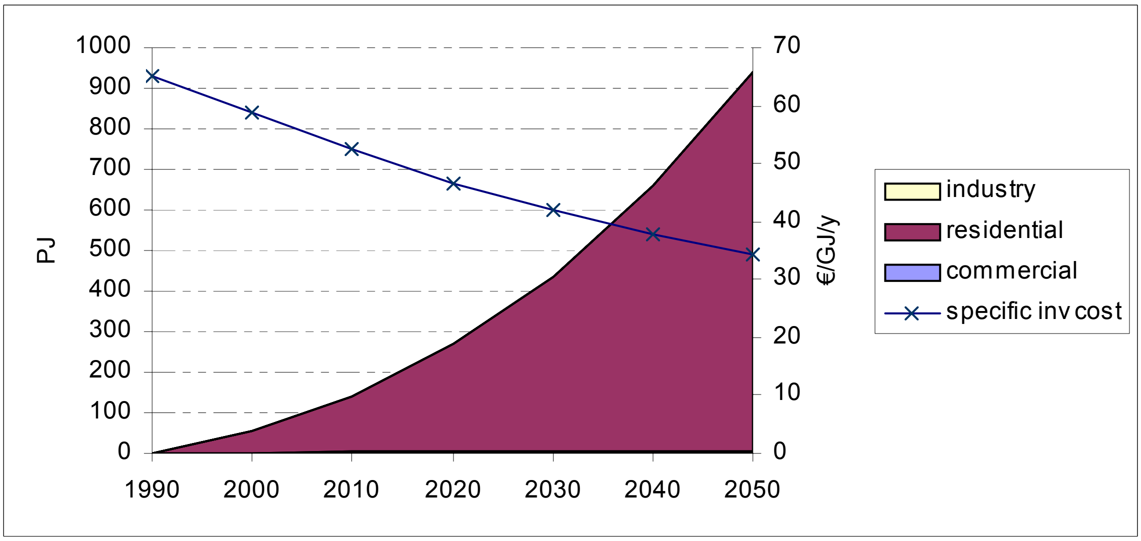
Figure 4-6: Gas engines: cumulative capacity (PJ/y) and investment cost development (€/GJ/y)



Heat Pumps

Heat pumps, in spite of having possible applications in all three sectors, only appear in practice in the residential sector. The cumulative capacity level of 920 PJ/y seems to be quite large, but compared to the total cumulative capacity level for residential heating applications, which amounts to about 70 000 PJ/y in 2050, it is quite small (~1%).

Figure 4-7: Heat pumps: cumulative capacity (PJ/y) and investment cost development (€/GJ/y)



CO_2 storage

CO_2 storage modelled as a specific key component for CO_2 injection, as part of CCS, appears in only one option, namely ECBM. Given the assumptions on fuel prices and CCS costs, this option proves to be the most economic due to the benefits of methane recovery as a result of its substitution in the coal seams by CO_2. Capture appears in both power sector and industry. In the power sector it is flue gas cap-ture on the advanced coal combustion plants, the cheapest option to produce electricity and capture large quantities of CO_2 in absence of a carbon constraint. The share of the industrial processes is small;

this is mostly capture of available highly concentrated CO_2 flows from ammonia and cement produc-tion.

Figure 4-8: CO_2 injection for storage: cumulative capacity (Mton/y) and investment cost development (€/ton/y)

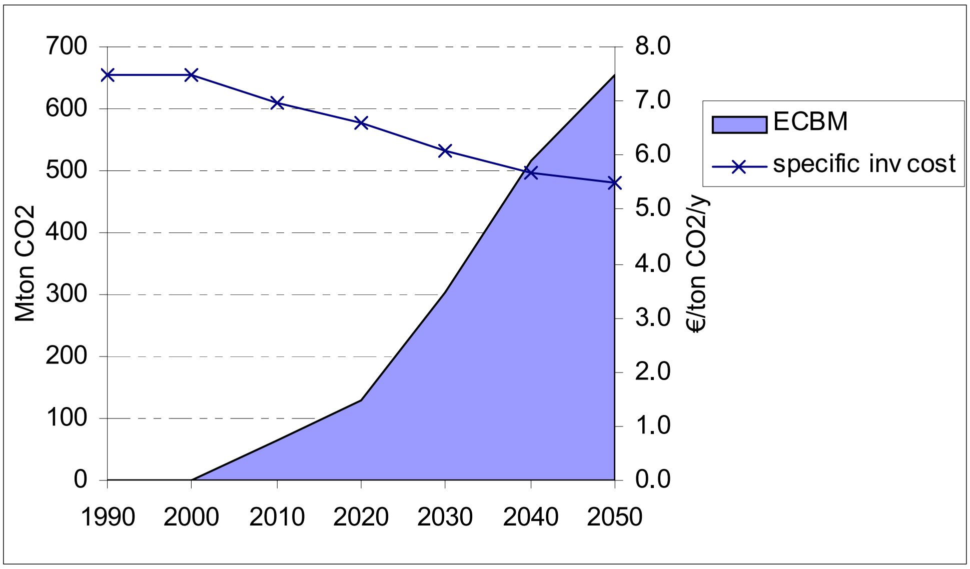
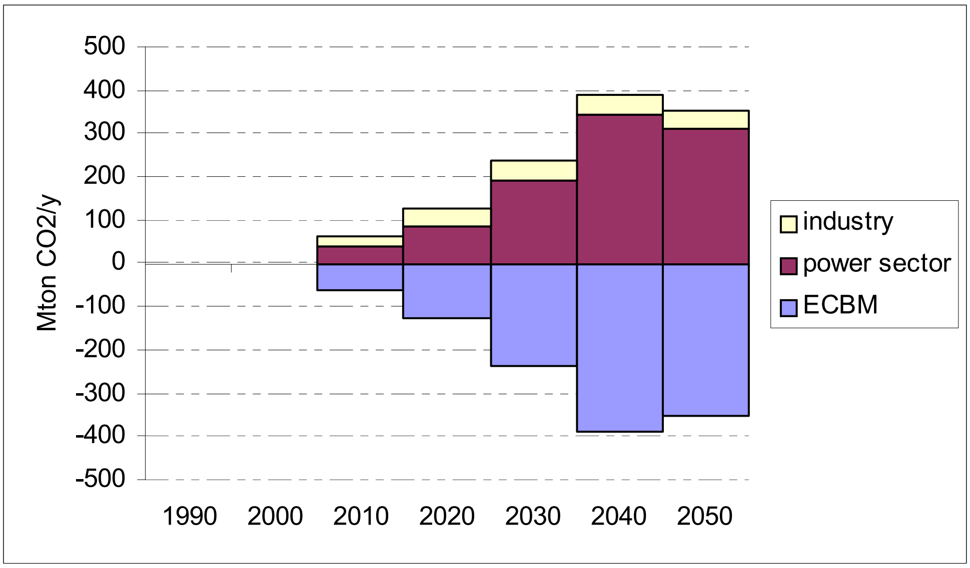


Figure 4-9: CO_2 capture and storage (Mton/y)



4.3. CO_2 policy cases

As mentioned before, two CO_2 policy cases, identified by a CO_2 price or tax, are analysed. The results of these cases will be represented together and they will be compared to the base or reference case.

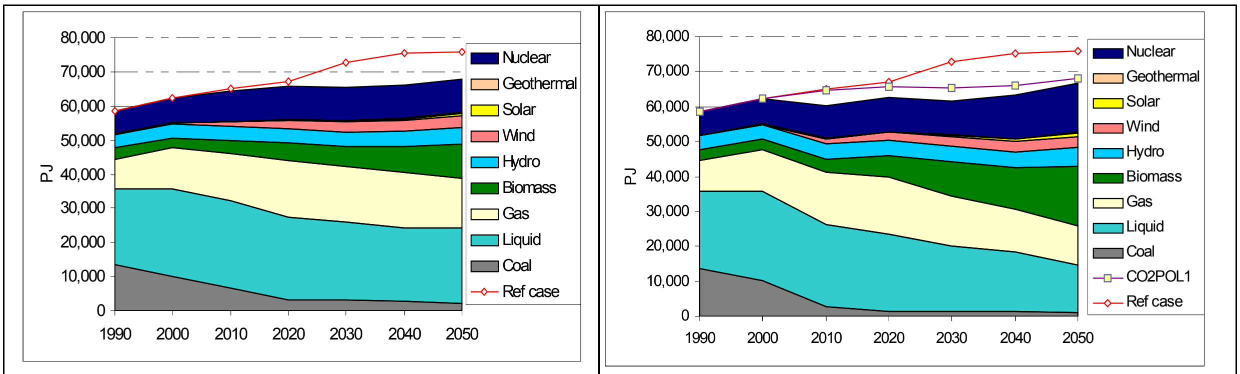
The cases are run with the price elastic demand option enabled. This means that under influence of changing commodity prices, the resulting final demand level (useful and final demand) may change. In particular, in carbon policy cases, the CO_2 tax will increase the price of fossil fuels, resulting in a tendency to use fuels or processes that cause less (or preferably no) CO_2 emissions. These technologies are generally more expensive than their fossil fuel alternatives, resulting in a more expensive output commodity. Aside from the impact on the use of specific fuels, demand levels could also drop since it could be more cost-effective to reduce demand than to pay a higher fuel price. This will lead to changes in the consumer and producers' surplus. This change will be used as proxy for the loss in GDP in the carbon policy cases.

The MARKAL model does not have the possibility to recycle taxes into the energy system, at least not without making additional assumptions (falling beyond the scope of this study) and not without doing iterative runs. The taxes generated hence disappear outside the energy system.

4.3.1. Primary energy and supply security

The introduction of the CO_2 taxes alters the energy system at its roots, namely the primary energy supply. This happens both in quantity and composition. The following figure represents the primary energy mix in both CO_2 cases. In both figures the level of the previous cases is included in order to enhance comparability.

***Figure 4-10:* Primary energy supply (PJ)**



(a) Primary energy in the CO2POL1 case

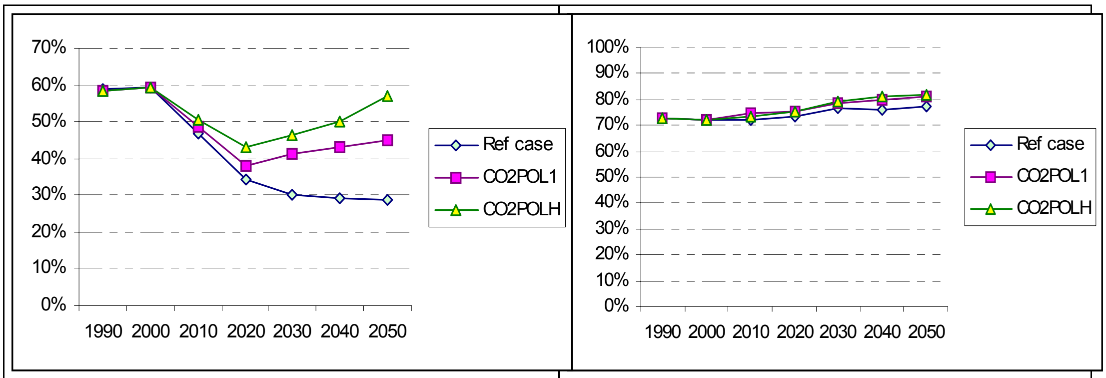
(b) Primary energy in the CO2POLH case

The CO_2 taxes reduce energy consumption in 2050 with about 8000 PJ in the CO_2POL case and 11000 PJ in the CO_2POLH case, i.e. reduce the consumption of primary energy by 10 to 15% compared to the base case. Coal disappears proportional to the CO_2 tax level and is almost gone by 2020; oil maintains its share due to the importance for transport although by 2050 it decreases somewhat in the higher tax case. The largest increase is to be found in the biomass supply, both domestic and import, and for wind and nuclear (limited). Hydro has no expansion potential, so its contribution stays stable. Solar appears at the end of the time horizon, but without major impact (hence very little deployment of solar PV learning).

Not only the level and the mix changes, also the composition domestic-import changes. The following graphs represent some of the SD indicators.

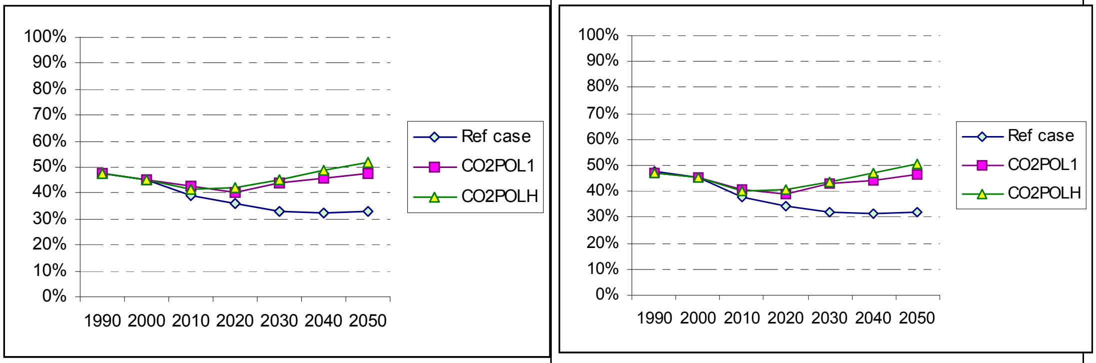
The import independency increases considerably with the tax introduction and moves towards 45% or even close to 60% in the CO_2POLH case, bringing it more or less back to the 1990 percentage by 2050. The first Shannon index on fuel diversity does not change much (a couple of %) although the fuel mix changes. There is still no even distribution of the fuels, some disappear (coal), some remain small (hydro, wind), some increase (biomass), all in all the diversity indicator hardly changes.

***Figure 4-11:* Supply security indicators**



(a) Import independency (domestic/total supply)

(b) Shannon index 1 (diversity)



(c) Shannon index 2 (import)

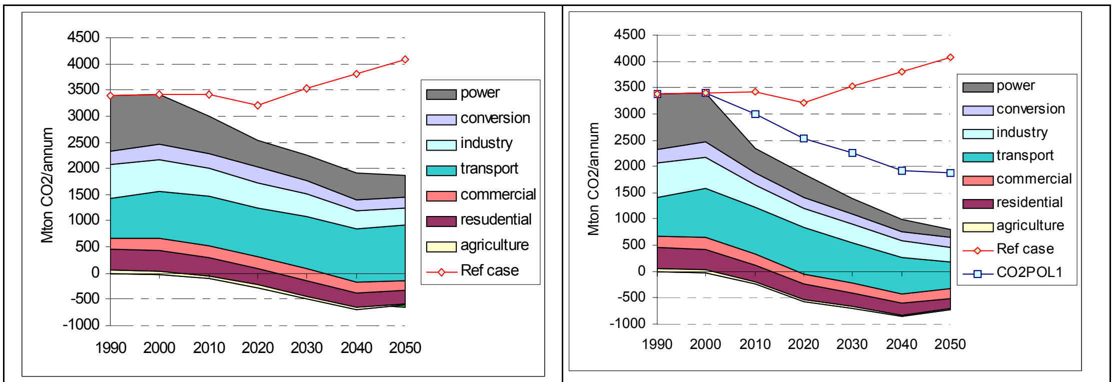
(d) Shannon index 3 (import stability)

The second and third Shannon index show much more improvement, values attain quite easily the current levels and show an increasing trend (compared to the down going trend in the reference case). Nevertheless a quite strong import dependency remains for Western Europe, mainly caused by the oil dependency (transport).

4.3.2. CO_2 emissions

As could be expected, CO_2 emissions are reduced by a considerable amount, even in the rather modest CO_2POL1 case. The relative reductions in net emissions by 2050 (including sinks and CCS) are about 54 and 80%. The largest reductions occur in the power sector, which also has the largest potential for CCS, and furthermore in fuel conversion and in industry. The built environment and transport reduce much less. CCS has an increasing role in the achievement of the net emission reduction, as well as the biological sinks. In 2050 CCS and sinks are responsible for halving the emissions (gross → net).

Figure 4-12 Sectoral CO_2 emissions (Mton/y)

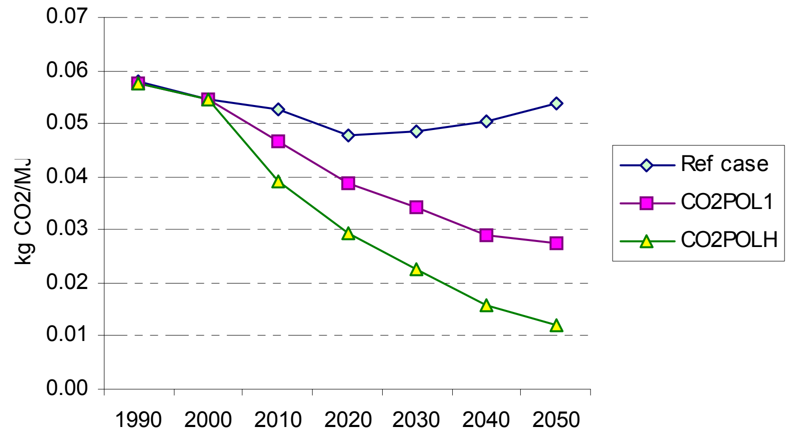


(a) Sectoral CO_2 emissions CO2POL1 case

(b) Sectoral CO_2 emissions CO2POLH case

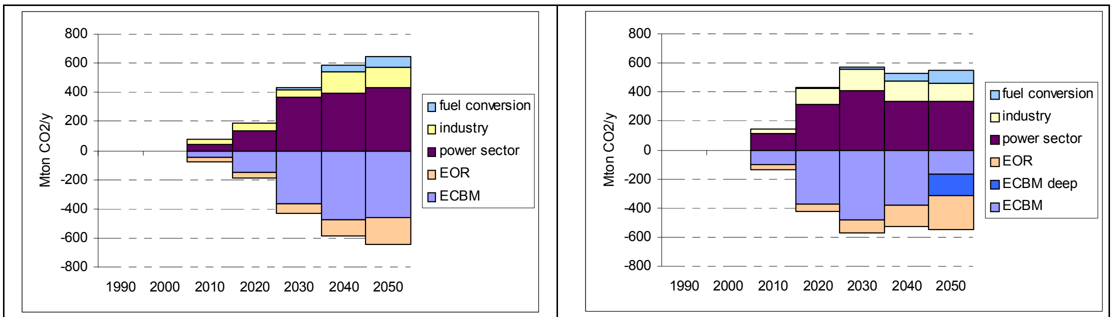
Combining the CO_2 emissions (net) with the primary energy supply, another indicator can be calculated: the CO_2 intensity of the primary supply (Figure 4-13). More biomass, wind and nuclear and less coal and oil cause the CO_2/MJ primary supply to drop two to five fold compared to the reference case by 2050.

***Figure 4-13:* CO_2 intensity of primary energy supply (kg/MJ)**



CCS becomes more and more important when introducing a CO_2 tax profile. CCS is introduced faster and to a larger extend with higher taxes, but once the economic beneficial potential of storage in ECBM and EOR is exhausted, CCS looses some of its attractiveness for CO_2 reduction (Figure 4-14). The capture appears still mainly in the power sector, although industry also increases the amount captured. Capture form fuel conversion (H_2 production) remains limited and only occurs from 2030-2040 onwards. The maximum remains at about 600 Mton/year stored from 2030 onwards.

Figure 4-14: **CO$_2$ capture and storage (Mton/y)**



(a) CO2POL1

(b) CO2POLH

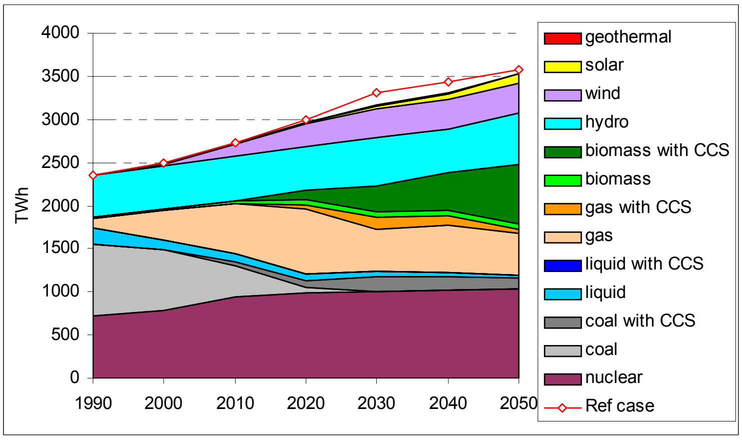
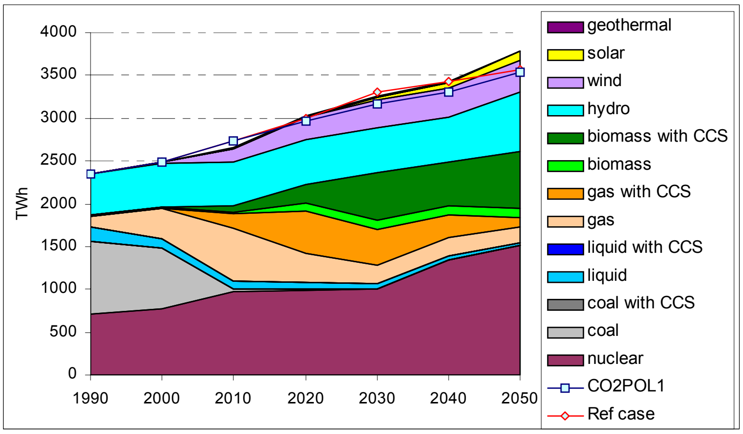
The storage reservoirs (ECBM, EOR) are used differently as shown in the previous figure. Since each reservoir has a limited capacity (see Annex 3), MARKAL will also optimise the use of it over the modeling horizon. As explained earlier, the actual model runs go up to 2080, in order to avoid end of term effects. This means that MARKAL will spread the use of the storage reservoirs over the period 2010 (start of CCS) to 2080. Results are only reported to 2050. The reservoirs are filled in CO$_2$POL1 up to 100% for ECBM (shallow coal fields only) and 25% for EOR, in CO$_2$POLH this is the same for ECBM, 10% for deep ECBM and 33% for EOR. In the reference case, the ECBM reservoir is used for 78% over the same period.

4.3.3. Electricity production

Like the primary energy mix, also electricity production changes under the CO$_2$ tax cases. As to the generation mix, the fossil fuel power generation sees the major changes. Coal and coal with CCS are completely replaced. Gas experiences a increasing shift to gas with CCS. A considerable increase occurs for nuclear and biomass fuelled power plants with CCS. Wind has now a noticeable part in the production, solar remains rather marginal.

The expected switch to electricity as potential emission free end use energy carrier is limited, and as a result the production level does not increase significantly. The lower CO$_2$ tax reduces total electricity production slightly, the taxes making it more expensive for the end users. This is however a relative effect because when the CO$_2$ taxes are increased, (CO$_2$POLH case) electricity production increases slightly as electricity now becomes an attractive substitute for other (fossil) energy carriers for the end users.

Figure 4-15: Electricity production according to input fuel (TWh)

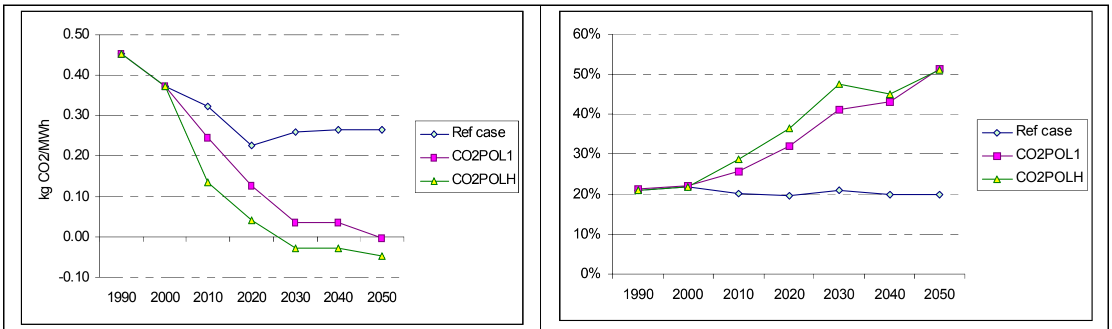
	(a) CO2POL1 case
	(b) CO2POLH case

The CO_2 tax and the effect of learning of the different components in the biomass power plants (gasifiers, combined cycle boilers, gas turbines and CO_2 capture units) make that the biomass-fuelled plants very quickly gain an important market share, even if the investment and operation costs are higher compared to fossil fuelled power plants with CCS. The biomass-fuelled plants are almost all equipped with CCS, leading to an emission free electricity production, or even a negative-emission production.

This quite remarkable success of biomass CCS plants, has yet another effect as well, namely on the CO_2 intensity of electricity. The introduction and deployment of these and other less or zero emission power plants cause a significant drop in the CO_2 intensity (Figure 4-15 (a)). At the end of time horizon, this intensity becomes even negative because the biomass plants capture more CO_2 than is emitted by the other plants. Biomass combustion by itself is regarded to be emission free (cfr. UNFCCC guidelines for emission inventories); the organic material contains carbon that is captured CO_2 from the atmosphere, and by storing the CO_2 from biomass combustion, the net CO_2 balance becomes negative. So biomass CCS plants serve as net storage options for CO_2.

Compared to the reference case, the share of renewables more than doubles by 2050 in both cases, reaching 50%. The largest increase occurs when a CO_2 tax is applied, increasing the tax results in a further increase, but smaller, by 2050 both tax cases reach the same share, the system has found a balance between base load, peak load and intermittent power generating plants that's satisfies the demand load curve.

Figure 4-16 **CO_2 intensity of electricity production (kg/MWh) and the share of renewable electricity production**



(a) CO_2 intensity electricity [kg CO_2/MWh]

(b) Share of renewables in electricity production

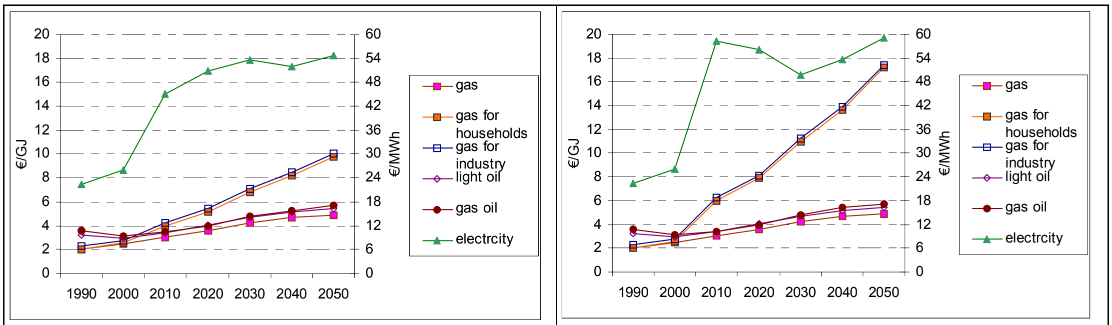
4.3.4. Marginal fuel costs

The CO_2 taxes clearly influence the fossil fuel marginal costs. Especially gas for end users sees a considerable increase. Overall gas' cost increases less because there is less demand from the power sector and in a linear supply and demand model like MARKAL, less demand leads to lower prices. For the end users, gas is apparently one of the solutions to respond to the restrictions posed by the CO_2 tax. Thus in these sectors demand for gas is increased, leading to higher marginal costs.

Oil and gas oil prices remain modest, again the higher CO_2 content of oil makes that there is less demand for it which on its turn does not trigger higher costs.

The price for electricity increases with about 2 to 4 €/MWh in the CO_2POL1 case, but much more in the CO_2POLH case. In the latter, the sharp rise in 2010 (when the tax is fully introduced) is caused by major changes in the power sector (fuel switch and new technologies). Later on the marginal cost is relaxed somewhat due to the longevity of the 2010 investments (life time of a couple of decades) and to the technology learning of the new investments.

Figure 4-17 **Marginal cost for gas, oil and electricity (€/GJ or €/MWh)**



(a) CO2POL1

(b) CO2POLH

4.3.5. Technology spill over

The next table contains the results of the learning components with cross-sectoral technology spill-over in both CO_2 tax scenarios. As in the reference case result analysis the emphasis lies on those key components which cover technologies in different sectors. These key component are: boilers, gas engines, heat pumps, CO_2 injection and CO_2 capture from coal. The latter occurs only in the tax scenarios and covers the power sector and the fuel conversion sector. The results in Table 4-6 need to be compared with the results from the reference case illustrated in Figure 4-5 to Figure 4-8. The results are given in extenso in order also to compare the outcomes of the CO_2POL1 case and the CO_2POLH case.

In general the results how that more advanced or CO_2 reducing technologies (heat pumps, CCS) are more deployed than in the reference case, i.e. they achieve a higher cumulative capacity by 2050. And more “traditional” fossil fuelled technologies (gas engines, boilers) become less deployed with higher CO_2 taxes.

The impact of the different levels of the CO_2 tax is rather limited, the results for the CO_2POLH case differ slightly from those of the CO_2POL1 case. In general, the CO_2 reducing technologies (heat pumps, and CCS) are deployed more, the fossil fueled ones (boilers, gas engines) less. The relative difference for the latter technologies is smaller than the difference for the CO_2 reducing technologies. A partially explanation for this is that the model structure is quite complex and that may technology and commodity interactions are not visible directly from the reported results, leading to outcomes with smaller differences than intuitively expected.

***Table 4-6* Results of key components in the CO_2 tax scenarios: cumulative capacity per sector and specific investment cost**

(a) Gas engine
CO2POL1 case

PJ cumulative capacity	**1990**	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
power sector	30	129	215	296	333	453	577
transport	12	607	1485	2816	3860	3860	3860
total	42	736	1700	3112	4193	4314	4437
specific inv cost							
€/GJ	494.77	291.96	231.83	194.76	178.44	178.39	178.34

CO2POLH case

PJ cumulative capacity	**1990**	**2000**	**2010**	**2020**	**2030**	**2040**	**2050**
power sector	30	129	215	263	275	295	307
transport	12	607	1445	2759	3870	3870	3870
total	42	736	1661	3021	4145	4165	4177
specific inv cost							
€/GJ	494.77	291.96	233.5	195.89	178.34	178.33	178.33

(b) Boilers
CO2POL1 case

GWe cumulative capacity	1990	2000	2010	2020	2030	2040	2050
power sector	103	128	136	152	167	172	177
large industry	32	48	77	98	127	132	142
small industry	20	23	45	49	70	73	93
total	155	199	257	300	365	377	412
specific inv cost							
€/kWe	508.49	508.11	507.64	507.31	506.84	506.76	506.52

CO2POLH case

GWe cumulative capacity	1990	2000	2010	2020	2030	2040	2050
power sector	103	128	135	146	148	149	155
large industry	32	48	73	92	108	113	122
small industry	20	23	44	45	66	66	86
total	155	199	251	283	321	328	364
specific inv cost							
€/kWe	508.49	508.11	507.69	507.44	507.15	507.1	506.85

(c) Heat Pumps
CO2POL1 case

PJ cumulative capacity	1990	2000	2010	2020	2030	2040	2050
commercial	0	0	3	3	3	132	529
residential	0	55	138	263	423	645	818
industry	0	0	0	0	0	0	283
total	0	55	141	266	426	777	1629

specific inv cost

€/GJ	64.98	58.77	52.53	46.82	42.16	36.17	29.32

CO2POLH case

PJ cumulative capacity	1990	2000	2010	2020	2030	2040	2050
commercial	0	0	0	0	113	195	345
residential	0	55	138	227	294	387	522
industry	0	0	0	0	370	525	912
total	0	55	138	227	777	1107	1779

specific inv cost

€/GJ	64.98	58.77	52.71	48.31	36.17	32.79	28.56

(d) CO$_2$ injection
CO2POL1 case

Mton cumulative capacity	1990	2000	2010	2020	2030	2040	2050
ECBM	0	0	50	149	415	746	876
EOR	0	0	26	42	94	153	275
total	0	0	75	191	509	899	1151

specific inv cost

€/ton CO$_2$	7.5	7.5	6.89	6.38	5.7	5.29	5.11

CO2POLH case

Mton cumulative capacity	1990	2000	2010	2020	2030	2040	2050
ECBM	0	0	101	369	582	750	750
ECBM deep	0	0	0	0	0	0	144
EOR	0	0	33	55	122	199	358
total	0	0	135	423	705	949	1252

specific inv cost

€/ton CO$_2$	7.5	7.5	6.59	5.83	5.46	5.25	5.05

(e) CO$_2$ capture from coal
CO2POL1 case

GWe cumulative capacity	1990	2000	2010	2020	2030	2040	2050
power sector	0	0	6	20	51	75	126
fuel conversion	0	0	0	2	13	34	67
total	0	0	6	22	64	109	194

specific inv cost

€/kWe	430	430	400.6	360.6	317.49	295.09	271.96

CO2POLH case

GWe cumulative capacity	1990	2000	2010	2020	2030	2040	2050
power sector	0	0	13	35	82	92	147
fuel conversion	0	0	0	0	11	37	78
total	0	0	13	35	93	129	224

specific inv cost

€/kWe	430	430	384.68	344.89	303.06	289.08	266.76

5. Outlook Using the POLES World Energy Model

5.1. World Oil and Gas resources

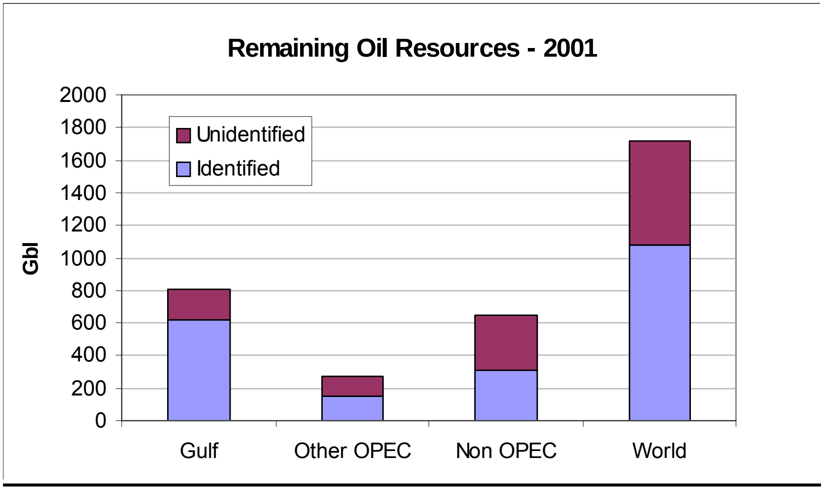
The assessment of oil and gas resources is the second set of key exogenous hypotheses for simulations in the POLES model. It is indeed critical as more and more studies point to the possibility of oil supply crisis, whether due to conjuncture and to insufficient capacity developments in the key supplying regions, or due to more structural factors such as the impossibility for reproduce reserves developments

In the present 2050 projection original estimates from USGS have been modified according to information provided by the Institut Français du Pétrole in a parallel POLES research project. This revision of the data set has not implied dramatic changes in the global picture, but it has allowed a precise checking and updating of data on resources and reserves on a country by country basis.

5.1.1. World oil resources

The new oil resource dataset indicate that, while more than 900 Gbl of oil have been produced today, identified reserves correspond to 1 100 Gbl and recoverable but yet to be identified resources may add 600 Gbl. Total recoverable oil is thus estimated to 2 600 Gbl, including past production. Of the 1 700 Gbl of oil that remains to be produced 800 come from the Gulf region and more than 200 from the other OPEC countries, which allows to insist on the strategic aspects of oil activities in those regions (see following figure).

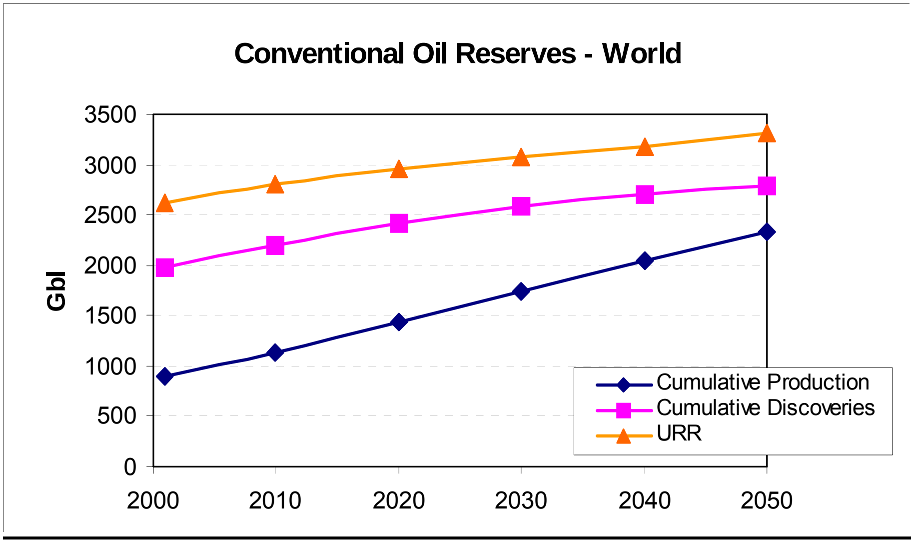
Figure 5-1: World oil identified reserves and unidentified recoverable resources (Gbl)



Source: POLES model hypotheses, from USGS and IFP

The POLES model however allows for a dynamic treatment of the oil discovery process and also integrates the consequences of technological progress on the quantities of oil that can be recovered from the different resources (which are dealt in a static way with a "reserve growth" factor in the USGS studies). Based on the dynamic impact of technological progress on the Recoverable Resources, and of the drilling activity on the discoveries on a region by region basis, the model allows to calculate remaining reserves as the difference of total discoveries and cumulative production to date.

Figure 5-2: The dynamics of oil recoverable resources and reserves (Gbl)



Source: Hypotheses from USGS and IFP and POLES model simulation

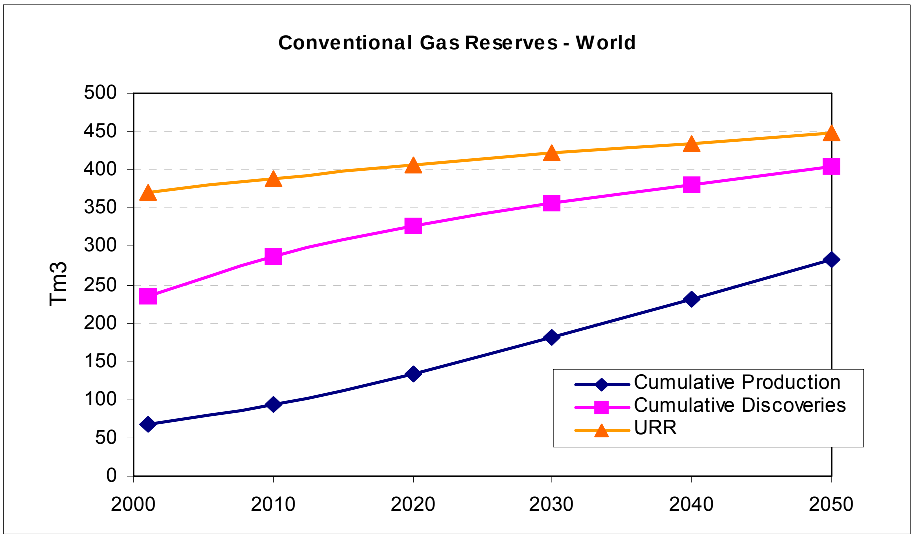
The figure above illustrates the dynamics in the model, while presenting the combined results of exogenous resource hypotheses and endogenous oil discovery process for the SAPIENTIA Reference projection. It allows to show how technological progress in recovery rates increases the URR from 2 600 Gbl today to 3 300 Gbl in 2050. This supplement of 700 Gbl, in the POLES model logics, confirms the USGS assessments according to which in the future the contribution to total resources of the "reserve growth" may equal that of the undiscovered reserves.

5.1.2. World gas resources

A very similar approach is used for the natural gas discovery and development process in the key gas producing countries. Figure 5-3 illustrates the peculiarities of the natural gas resource profile compared to that of oil:

- The gain in Recoverable Resources due to technological progress is limited in the case of natural gas as the margins from recovery rate improvements are smaller than in the case of oil.
- However, at the starting of the simulation the ratio of cumulative production to Recoverable Resources is lower, i.e. 18 % only for gas against 32 % for oil, indicating that up to now gas resources have been less exploited than those of oil.
- This is also confirmed by the analysis of the time horizon at which cumulative production equals half the Recoverable Resources, which happens to be shortly after 2020 in the case of oil and only before 2040 in the case of natural gas.

Figure 5-3: The dynamics of natural gas recoverable resources and reserves (Tm3)



Source: Hypotheses from USGS and IFP and POLES model simulation

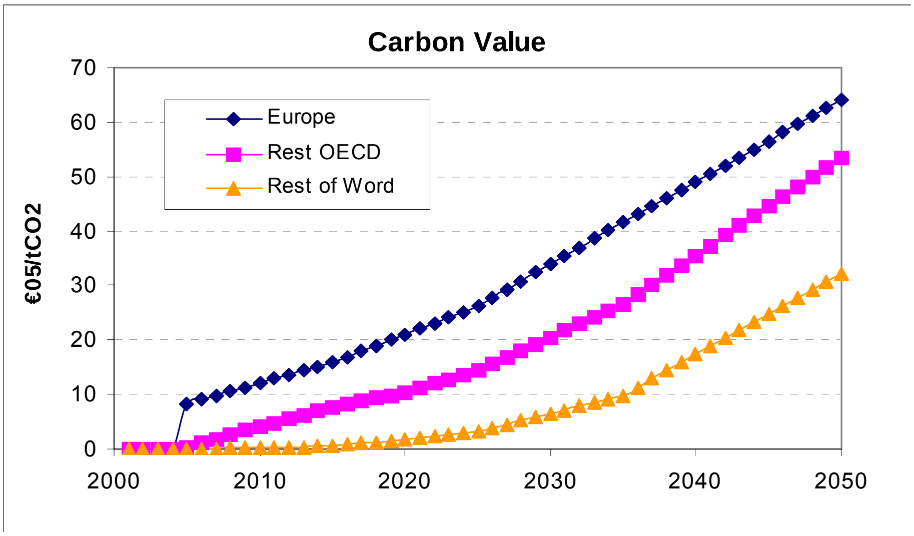
This last issue is considered as an essential benchmark for the proponents of application at the global level of the Hubbert's theory of the "peak oil". They indeed consider that total production should begin to peak and decline when cumulative production equals half the total recoverable resource. The oil and gas world production profiles are analyzed below in this report. At that stage, it probably suffices to say that the oil and gas resource constraints may begin to be operative within the time-frame of this projection and that this will happen with a ten to fifteen years of antecedence for oil compared to natural gas.

5.2. Climate policies, CO_2 abatement and carbon value

While oil and gas resources build the "upstream" constraint to world energy development to 2050, CO_2 emission policies will probably build the "downstream" constraint. The study of the dynamic interactions between these two different sets of constraints is probably one key issue for the understanding of the future of world energy. In the POLES model, the impacts of CO_2 emission constraints can be studied either through the introduction of a given emission profile at the regional or global level or through the introduction of a carbon value (reflecting a carbon tax or the price of the permit in an emission quotas trading system). The latter solution has been adopted in the SAPIENTIA project which focuses not on the definition of international targets and associated climate regime, but rather on the impacts of emission reduction policies on technology development, independently of distributional impacts associated to target endowments.

The DELPHI study organized by ICCS-NTUA in the SAPIENTIA project has allowed to identify the carbon values that may reflect emission abatement policies in the different regions of the world. While the SAPIENTIA DELPHI provides carbon values with probabilistic attribute, defined by for the intensity of the effort in each region and the conditional probabilities of action across regions, the deterministic simulation with the POLES model uses the mean estimate for the carbon values in Europe, the rest of OECD countries and the Rest of the World, as illustrated in the following figure.

Figure 5-4: Carbon values in the world regions according to SAPIENTIA DELPHI



Source: SAPIENTIA ICCS Delphi study

The resulting scenario hypotheses correspond to a regularly increasing Carbon value, rising for Europe from 12 €/tCO_2 in 2010, to 33 in 2030 and 64 in 2050. The other regions follow a similar path with a time-lag in the carbon value of less than ten years for the Rest of OECD compared to Europe and of more than ten years for the Rest of the World compared to the Rest of OECD.

5.3. Technology portfolios in the POLES – SAPIENTIA version

Technological change is a key dimension of any energy scenario, in particular when long term time horizons and strong constraints – on resources and/or on emissions – are considered. The mastering of these constraints will indeed necessitate the introduction of new technologies that represent in most cases technological breakthroughs or radical innovations from today’s situation.

For the SAPIENTIA project, new energy technology portfolios have been added to the one already existing in the 2030 version of the model, i.e. large scale power generation and renewable electricity. The corresponding new modelling in POLES is described in the POLES SAPIENTIA extension report. The new portfolios are:

- Hydrogen production through chemical, thermo-chemical or electrical routes.
- Carbon Capture and Storage options to be used as add-ons in fossil-based power generation or hydrogen production generation plants.
- A set of distributed electricity production systems with or without cogeneration, from fossil, renewable or hydrogen carriers.
- Very Low Emission Vehicles with new power system and carrier concepts (in particular different types of electric and hydrogen cars).
- Very Low Energy Buildings with significantly improved thermal performances (Factor 2 to 4 reduction from existing buildings in each region); provide positive energy buildings when combined with building integrated PV systems.

Table 5-1: Energy technologies considered in the POLES model

Large Scale Power Generation
Conventional, large-size hydroelectricity
Conventional Light-Water nuclear Reactor
New Nuclear Design
Pressurised coal supercritical
Pressurised coal supercritical with sequestration
Integrated Coal Gasification with Combined Cycle
Integrated Coal Gasification with Combined Cycle with sequestration
Advanced Thermodynamic Cycle (coal powered)
Lignite-powered Conventional Thermal
Coal-powered Conventional Thermal
Oil-powered Conventional Thermal
Gas-powered Conventional Thermal
Gas-powered Gas Turbine
Oil-powered Gas Turbine in Combined Cycle
Gas-powered Gas Turbine in Combined Cycle
Gas-powered Gas Turbine in Combined Cycle with sequestration
New and Renewable Energy Systems
Small Hydro Power plants (<10 MWe)
Wind power plants for network electricity production according to wind resources
Offshore Wind power plants
Solar Power Plants (thermal technologies for network electricity production)
Low Temperature Solar systems in residential sector
Biofuels, conventional technologies (woodfuels, elec. from wastes, biofuels)
Biomass gasification for electricity production in GT
Distributed Power Generation
Combined Heat and Power (small to medium-size cogeneration in industry)
Stationary Fuel Cells with natural gas
Stationary Fuel Cells with hydrogen
Decentralised building integrated PV systems with network connection
PV systems for Decentralised rural electrification in DCs
Hydrogen production
Hydrogen from Gas Steam Reforming
Hydrogen from Gas Steam Reforming with CCS
Hydrogen from Coal Partial Oxidation
Hydrogen from Coal Partial Oxidation with CCS
Biomass PYrolysis
Hydrogen from Solar thermal High-temperature Thermolysis
Hydrogen from Nuclear thermal High-temperature Thermolysis
Hydrogen from Water Electrolysis dedicated Nuclear power plant
Hydrogen from Water Electrolysis dedicated Wind power plant
Hydrogen from Water Electrolysis baseload electricity from Grid
Very Low Emission Vehicles
Conventional Internal Comb. Engine
Hybrid (pluggable)
Electric (battery)
Gas fuel cell vehicle
Hydrogen fuel cell vehicle
Hydrogen in conventional ICE

Data for the simulation of endogenous technical change have been organised in a dedicated database, called TECHPOL. This database is described in the TECHPOL database report. It allows in particular to greatly enhance the consistency of the hypotheses across the different technologies.

5.4. PRIMARY ENERGY TRENDS – WORLD AND MAIN REGIONS

The SAPIENTIA Reference energy projection provides a detailed image of the world energy system, which accounts for the drivers and constraints described in the above section and uses the endogenous technology dynamics defined in the SAPIENTIA project, with Two Factor Learning Curves and clustering effects.

The outcome corresponds to a world energy system that expands in a relatively homogenous way until 2020, but then incur increasing structural changes, first with the impact of the peak oil by 2030, then with the accelerated diffusion of renewable, nuclear energy and Carbon Capture and Storage technologies between 2030 and 2050.

5.4.1. World primary energy consumption

The growth in world primary energy consumption is expected to progressively slow down, from 2.2 %/yr in the current decade, to 1.7 %/yr between 2010 and 2030 and 1.3 %/yr between 2030 and 2050. In spite of the slowdown, the level of total primary energy consumption more than doubles from current level, to 22.3 Gtoe in 2050 (see table below).

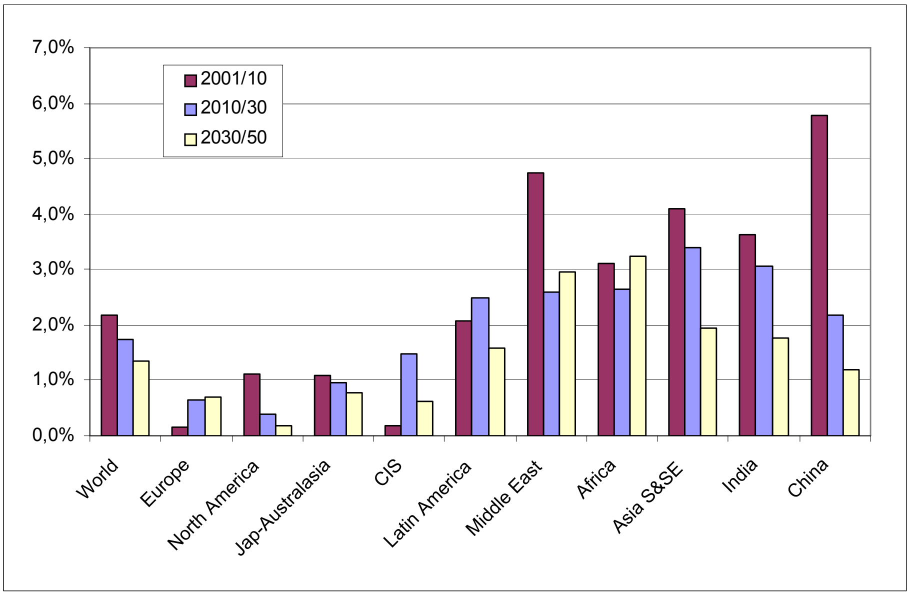
Table 5-2: Primary energy consumption, world and key regions (Mtoe)

						Annual % change		
	2001	**2010**	**2020**	**2030**	**2050**	***2001/10***	***2010/30***	***2030/50***
World	**9955**	**12097**	**14578**	**17049**	**22338**	**2,2%**	**1,7%**	**1,4%**
Europe	1927	1956	2099	2230	2569	0,2%	0,7%	0,7%
North America	2525	2791	2924	3012	3118	1,1%	0,4%	0,2%
Jap-Australasia	648	714	785	865	1011	1,1%	1,0%	0,8%
CIS	926	941	1125	1262	1430	0,2%	1,5%	0,6%
Latin America	614	738	982	1208	1650	2,1%	2,5%	1,6%
Middle East	379	575	735	958	1713	4,8%	2,6%	2,9%
Africa	478	629	825	1063	2017	3,1%	2,7%	3,3%
Asia S&SE	802	1150	1683	2244	3301	4,1%	3,4%	1,9%
India	524	723	1023	1319	1870	3,6%	3,1%	1,8%
China	1133	1880	2397	2886	3659	5,8%	2,2%	1,2%

Source: POLES model, SAPIENTIA-ref

The regional dynamics are much contrasted in the beginning of the simulation, with yearly average growth rates between 3 and 6 %/yr in all developing or emerging regions but Latin America and of 1 % or less in the Annex 1 regions. The differences are somewhat smaller in the following periods as total energy consumption growth rates diminish in all regions but proportionally more in the Non-Annex 1 regions. Between 2030 and 2050 primary consumption growth rates are below 2 %/yr in all developing regions but Africa and Middle East and below 1 %/yr in all industrialized regions (see following figure).

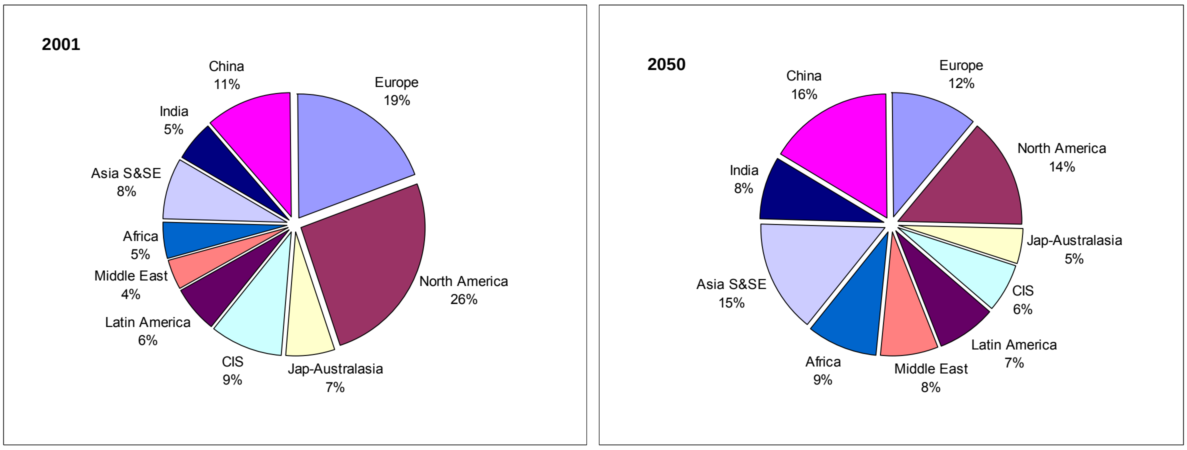
Figure 5-5: Primary energy consumption growth, world and key regions (%/yr)



Source: POLES model, SAPIENTIA-ref

Of those different regional dynamics a fully different energy world emerges in 2050. The share of Annex 1 countries, which now represents 61 % of world total energy consumption, is brought down to only 37 % of world total in 2050. By that date Asia's share is of 41 % and that of the rest of the developing regions of 24 %.

Figure 5-6: World energy consumption by region, 2001 and 2050



Source: POLES model, SAPIENTIA-ref

Europe, North America, China and India represent half of total world energy consumption, which is less than their share in world product. This is explained by the fact that four of the remaining regions present relatively higher energy intensities: the CIS and Middle-East as large energy producing and exporting regions and Africa and Rest of Asia, as regions with relatively low-GDP per capita and high energy intensity (Table 1-2 and Table 5-3).

Trends in energy intensities at world level show a regular decrease in all regions and all periods, except for the middle-East between 1990 and 2010. In spite of a slowdown by the end of the period, this global trend results in a world energy intensity in 2050 that is almost halved from today's level (Table 5-3).

Table 5-3: Energy intensity, world and key regions (koe/103€99)

						Annual % change		
	2001	2010	2020	2030	2050	2001/10	2010/30	2030/50
World	**236**	**203**	**179**	**161**	**136**	**-1,6%**	**-1,2%**	**-0,8%**
Europe	187	154	132	117	102	-2,1%	-1,4%	-0,7%
North America	252	211	178	152	116	-2,0%	-1,6%	-1,3%
Jap-Australasia	181	159	143	132	116	-1,4%	-0,9%	-0,6%
CIS	633	435	370	327	261	-4,1%	-1,4%	-1,1%
Latin America	180	165	158	148	130	-1,0%	-0,5%	-0,6%
Middle East	387	425	371	337	290	1,0%	-1,1%	-0,8%
Africa	287	280	266	255	229	-0,3%	-0,5%	-0,5%
Asia S&SE	247	232	220	204	170	-0,7%	-0,6%	-0,9%
India	190	149	128	114	92	-2,6%	-1,3%	-1,1%
China	236	206	174	153	119	-1,5%	-1,5%	-1,2%

Source: POLES model, SAPIENTIA-ref

5.4.2. World primary supply by source

World energy supply incur very significant structural changes all over the projection period, which reflects the complexity of the dynamic interactions between the drivers and constraints to the development of the world energy system. The key changes in world energy supply can be synthesized as follows:

- Over the whole projection period, in spite of rising CO_2 emission constraints and carbon value coal but thanks to a significant use of Carbon Capture and Storage, coal is bound to a come back as the key primary energy source at world level.
- Conversely, and in spite of significant amounts of non conventional resources and production in this projection the dynamics of oil production and consumption will be severely constrained by the growing scarcity of new reserves outside the Middle-East region, which translates in strongly increasing oil prices in this projection. The peak oil occurs by 2030 for conventional oil, 2040 for total oil production.
- The situation of natural gas is less constrained at the beginning of the simulation, but progressively, gas also turns into a constrained energy, with a peak in production occurring shortly after 2040.
- After 2010, nuclear energy is rapidly growing, even more rapidly than coal and its contribution to world energy supply is multiplied by more than four until 2050.
- Similarly this projection corresponds to a very significant projection of renewable energies. When large hydro, biomass, wind and solar energy are taken altogether, the contribution of renewable energies to world supply is of 3.52 Gtoe, that is, slightly more than nuclear energy.
- The dynamics are however highly differentiated among the renewable themselves, with a low but regular increase for hydro, a slowdown for biomass followed by an acceleration when new biomass technologies develop, and finally a constantly rapid diffusion for solar and particularly wind technologies at more than 10 %/yr before 2030, 8 %/yr after.

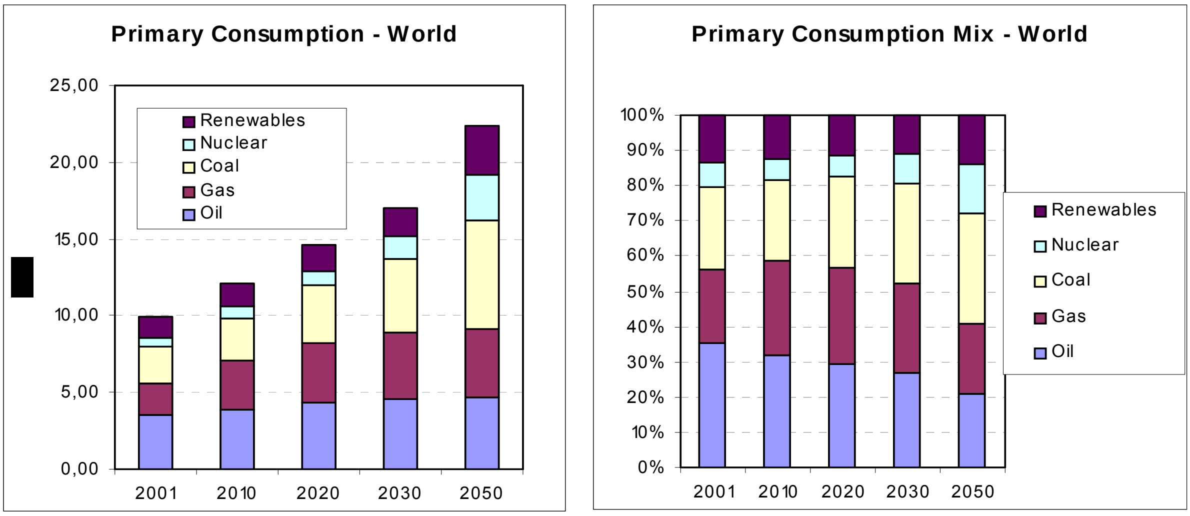
Table 5-4: World primary energy production (Mtoe)

						Annual % change		
	2001	**2010**	**2020**	**2030**	**2050**	***2001/10***	***2010/30***	***2030/50***
Primary Production (Mtoe)	10230	12248	14747	17227	22520	2,0%	1,7%	1,3%
Coal, lignite	2408	2764	3771	4822	7017	1,5%	2,8%	1,9%
Oil	3711	3989	4484	4745	4810	0,8%	0,9%	0,1%
Natural gas	2094	3263	3958	4355	4514	5,1%	1,5%	0,2%
Nuclear	671	728	889	1424	3024	0,9%	3,4%	3,8%
Hydro, geothermal	232	274	313	349	415	1,8%	1,2%	0,9%
Biomass and wastes	1106	1209	1266	1353	1952	1,0%	0,6%	1,8%
Wind, solar	7	21	67	179	788	12,8%	11,2%	7,7%

Source: POLES model, SAPIENTIA-ref

The corresponding changes in the market shares of the different primary sources are indeed significant. Basically, and when the 2050 situation is compared with the one of 2010, non-fossil sources increase from 20 % to 30 % of total supply, while oil and gas share decrease from 60 % to 40 %; as a consequence, the share of coal increase of about 10 points of percentage, from more than 20 % to 30 % (following figure).

Figure 5-7: World energy consumption by primary source



Source: POLES model, SAPIENTIA-ref

5.4.3. The long term oil production profile

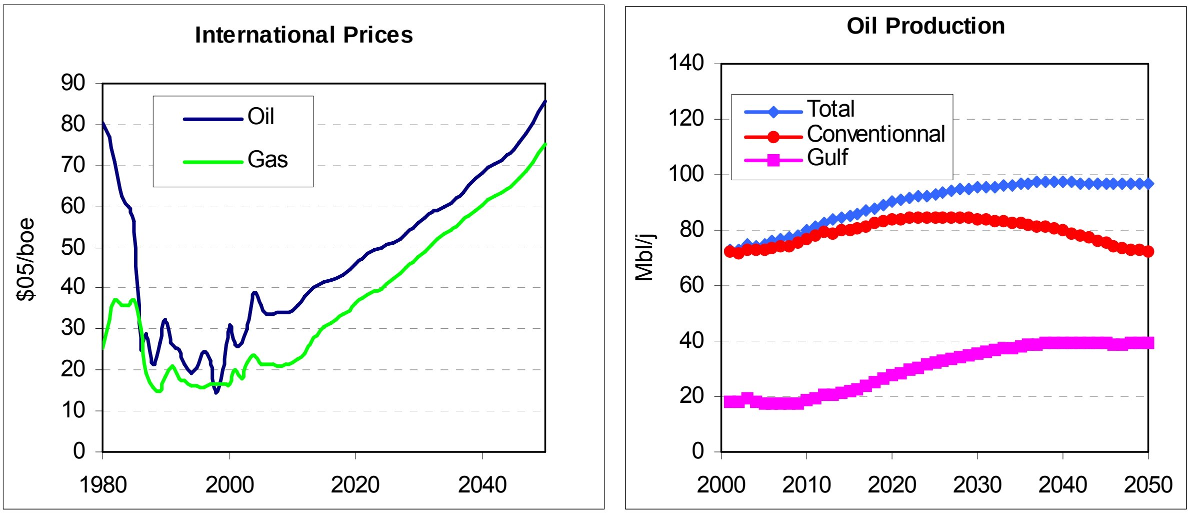
The oil price and production profiles are structuring elements for any long term energy projection, as oil – due to its easy transport and storage properties – has been since a long time the swing primary energy at world level. In parallel, the price of oil was the leading price for all other energy sources. While short term demand and supply balance problems push the oil price up, some observers even announce the imminence of a “peak oil” that would translate in the impossibility to increase world oil production.

Fears of oil scarcity have been regularly denied by actual evolutions in the past, but the real difficulties encountered today in reproducing non OPEC reserves and increasing OPEC production capacities, point to the possibility of the entry into a structurally new oil era. With the disappearance of the spare capacities that existed since the oil shocks of the early seventies the probability of the persistence of frequent difficulties in managing the supply and demand balance seems to be high.

Although the SAPIENTIA energy projection doesn't depict crisis scenarios, it however takes account of this new situation, through high oil prices: 45 $/bl in 2020, 55 in 2030, 85 in 2050 (Figure 5-8 left). These price levels strongly constrain oil demand and result in a production profile that is consistent with the assessment of possible future oil development (Figure 5-8 right):

- Until 2010 some increase in non-Gulf production can be expected from development in the CIS, while the non-Gulf and non-CIS regions' production is already decreasing.
- After that date non-Gulf production peaks and then regularly decreases over the projection period.
- The peak in total conventional oil occurs between 2020 and 2030
- Meanwhile the Gulf oil production doubles and reaches 40 Mbd in 2040, while non conventional oil also rises and represents 20 Mbd in 2040
- Between 2040 and 2050 total oil production is stabilised with non conventional oil compensating for the continuous decline in non-Gulf production

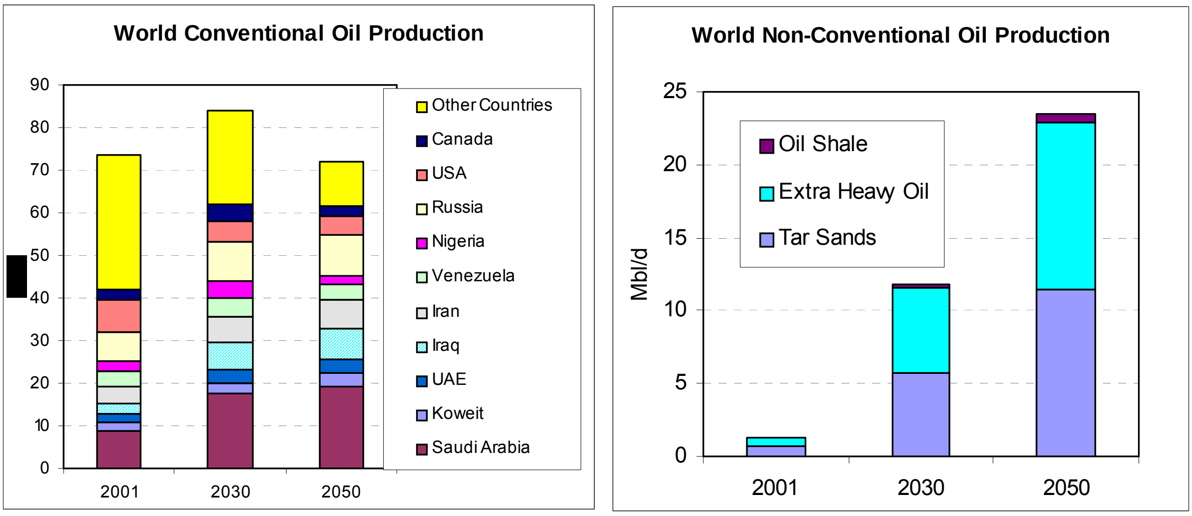
Figure 5-8 International energy prices and oil production profiles



Source: POLES model, SAPIENTIA-ref

Due to the relative exhaustion of non-OPEC reserves, world oil production is expected to progressively concentrate in a limited number of countries. The ten largest oil producer – among which the only non-OPEC are Russia, the USA and Canada – will represent almost 75 % of total world oil prduction in 2030 and 85 % in 2050 (Figure 5-9). In 2050, non conventional oil represent 23 Gbl – i.e. the equivalent of the current Gulf production – almost equally divided among Tar Sands (Canada) and Extra Heavy Oil (Venezuela).

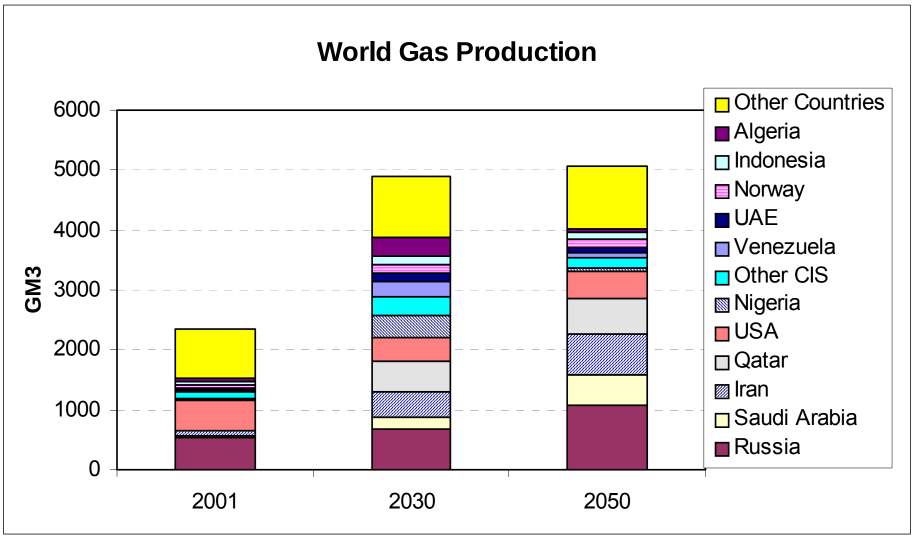
Figure 5-9: World oil production, conventional and non-conventional



Source: POLES model, SAPIENTIA-ref

World gas production will also incur a double process of "peaking" around 2040 and of regional concentration, with the ten largest producers representing 80 % of total production after 2030. Among this ten largest, five will play a key role with 70 % of total production, Russia, Saudi Arabia, Iran, Qatar and the US (Figure 5-10).

Figure 5-10: World Natural gas production

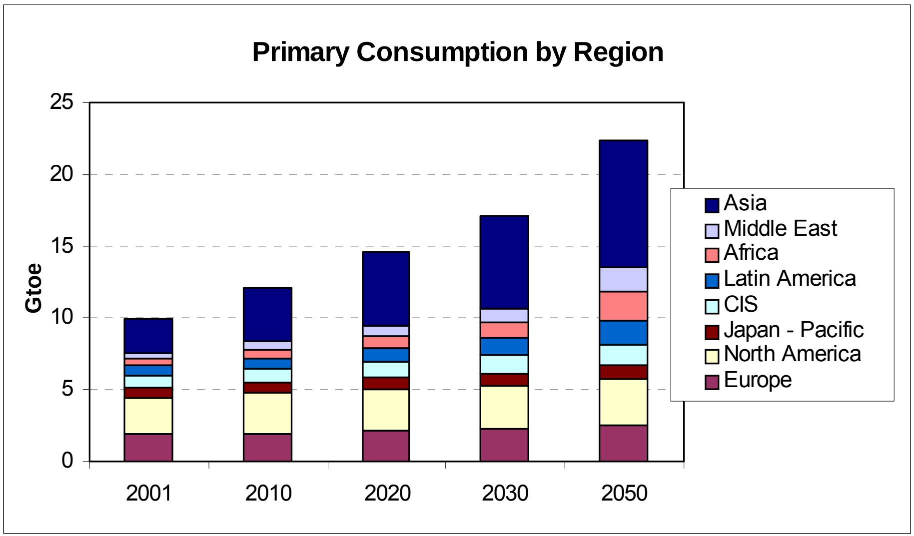


Source: POLES model, SAPIENTIA-ref

5.4.4. Primary consumption by region and world energy trade

While world primary energy consumption is multiplied by a factor of 2.2 along the projection period, the increase is of only 35% in the industrialised or "Annex 1" countries. The multiplication factor is of 2.7 for Latin America, 3.7 for Asia, 4.2 for Africa and 4.5 for the Middle East. From now to 2050 the increase in the developing regions' energy demand represents more than 80% of the total world increase (Figure 5-11).

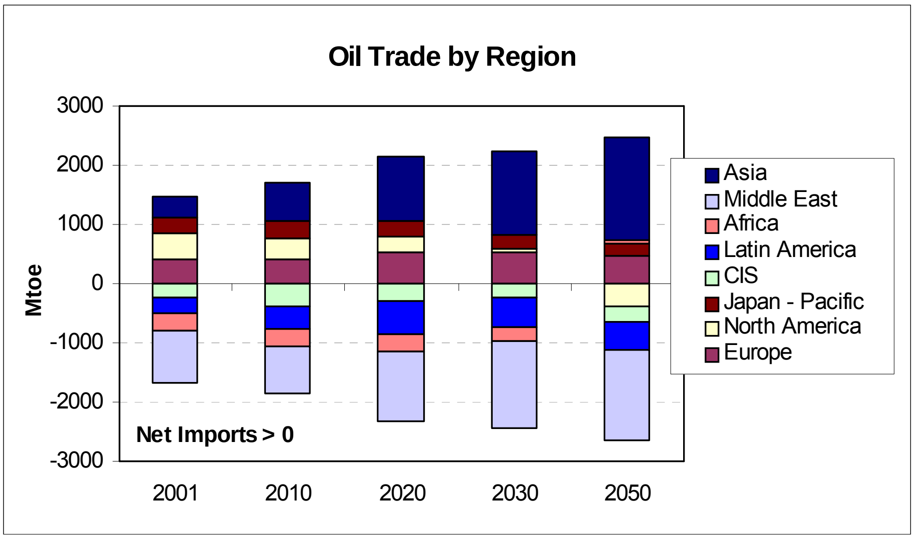
Figure 5-11: World energy consumption by region



Source: POLES model, SAPIENTIA-ref

As a result of each region's energy demand and resource endowment, in ternational energy trade will grow significantly in the next half century. In spite of and also due to the peak oil, oil trade will have almost doubled in 2050, from 1.4 to 2.5 Gtoe. Asia will be the main importing region followed by Europe and Japan-Pacific. Among the net exporting regions one reports of course the Middle East followed by Latin America, North America (largely thanks to Canadian tar sands) and the CIS (Figure 5-12).

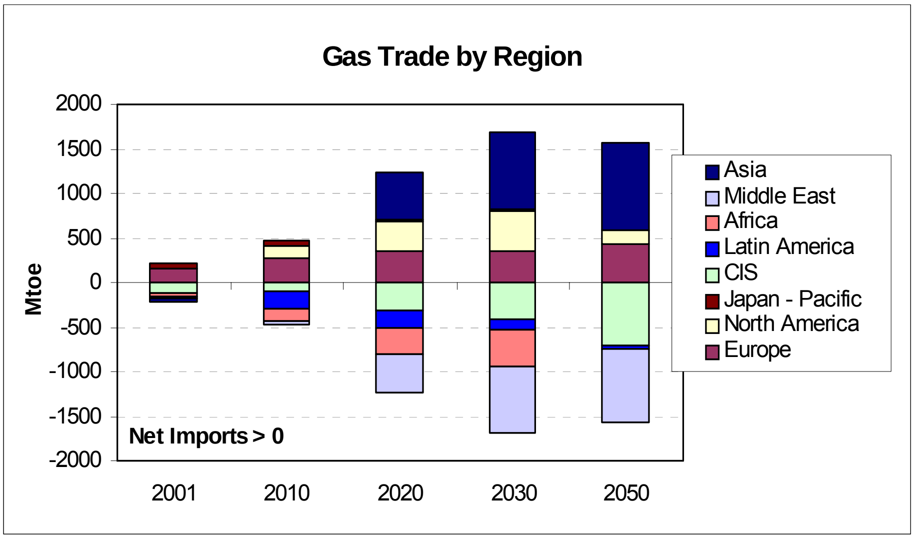
Figure 5-12: Inter-regional oil trade



Source: POLES model, SAPIENTIA-ref

International gas trade also incurs an impressive development in the period considered, rising from the current 200 Mtoe, to 1.7 Gtoe in 2030 and then 1.6 Gtoe in 2050. From 2020 onwards, Asia is the first gas importing region, with North America emerging as a major importing region, as soon as in 2010. The net imports of Europe are relatively stable at around 300-400 Gtoe per year.

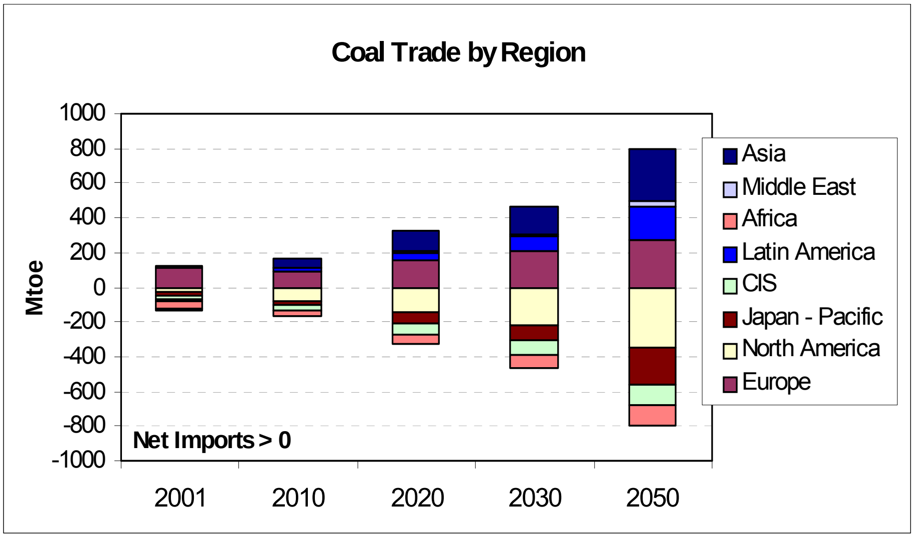
Figure 5-13: Inter-regional natural gas trade



Source: POLES model, SAPIENTIA-ref

Coal trade follows line with a rapidly increasing international trade, from current 150 Mtoe to 800 Mtoe in 2050. While Europe is today by far the first coal exporter, its relative weight decreases as Asia emerges as major coal importing region, followed by Latin America after 2020. North America becomes a key exporting region after 2010, as does the Pacific region (through Australia) after 2020. Coal exports are complemented by the CIS and Africa (South Africa)

Figure 5-14: Inter-regional coal trade



Source: POLES model, SAPIENTIA-ref

This part of the energy outlook provides an image of a rapidly changing international energy world, with in spite of the peaking of oil and gas production, international flows increase for all primary fuels, resulting in a world inter-regional energy trade of 4.8 Gtoe – with the regional delimitation adopted here – compared with 1.8 Gtoe today.

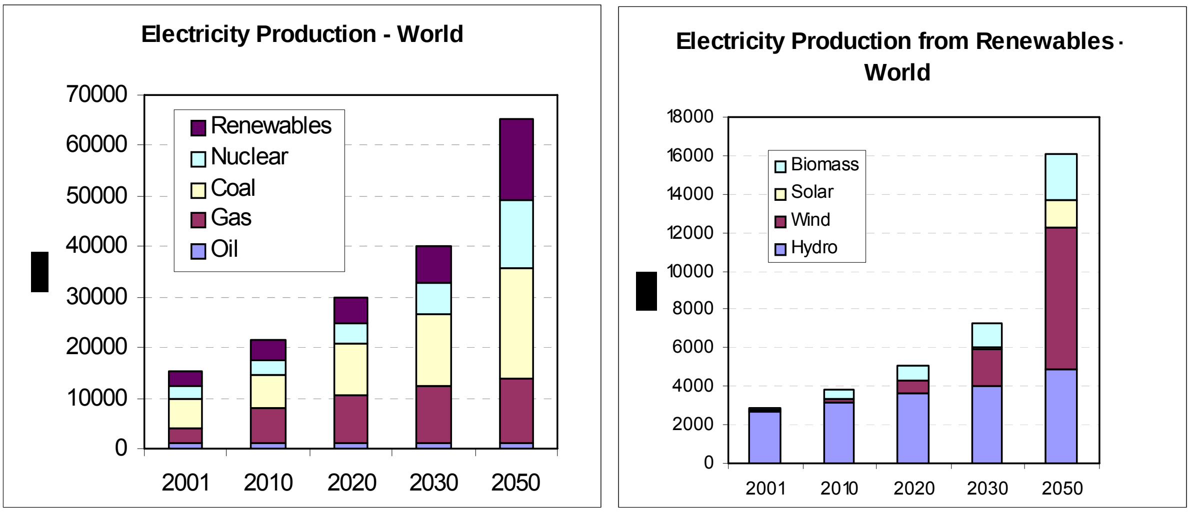
5.5. Energy Technology Outlook

The key factors in the development of the world electricity sector in the next decades are the growth differentials across world regions, the changes in primary energy supply and prices, the trends in technological developments. Indeed the development of electricity is impressive, however the structure of power generation is relatively stable in this Reference projection.

5.5.1. Power generation technologies

Over the next half of a century, electricity production increase will broadly follow economic growth, with a first doubling of total generation between now and 2020 and a second doubling until 2050. All primary sources contribute to the corresponding increase in production except oil, which is too expensive and concentrated in other uses (Figure 5-15 right). Electricity from renewable also quadruples, mostly thanks to increases in wind energy (on and offshore), but also with a significant contribution of electricity from solar and biomass sources (Figure 5-15 left).

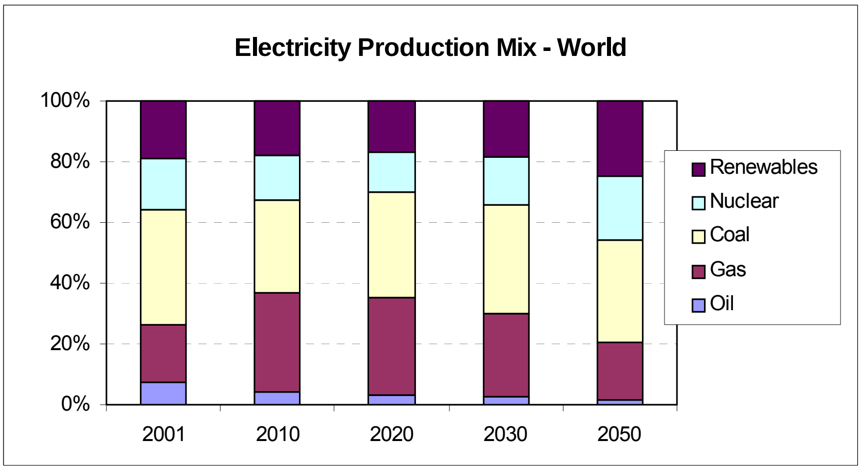
Figure 5-15 World electricity production by source



Source: POLES model, SAPIENTIA-ref

The relative weight of the different primary energy in the electricity fuel-mix changes in the process, but not in a dramatic way: the share of gas increases to 30% in 2020 but goes back to its current level of 20% in 2050; coal's share is between 30 to 40 % and the increase in nuclear and renewable (at more than 20% each) compensate for the disappearing of oil from the power generation sector.

Figure 5-16: World electricity production by source, market shares



Source: POLES model, SAPIENTIA-ref

The increase in total installed capacities is more rapid still than the increase in production and this is largely due the development of renewable, which due to intermittency display a lower average load factor than the other plant categories (Table 5-5). Among coal-based power generation plants one can notice the rapid growth of new advanced technologies, which represent more than half the total installed capacities in 2020.

Table 5-5: World power generation installed capacities and production

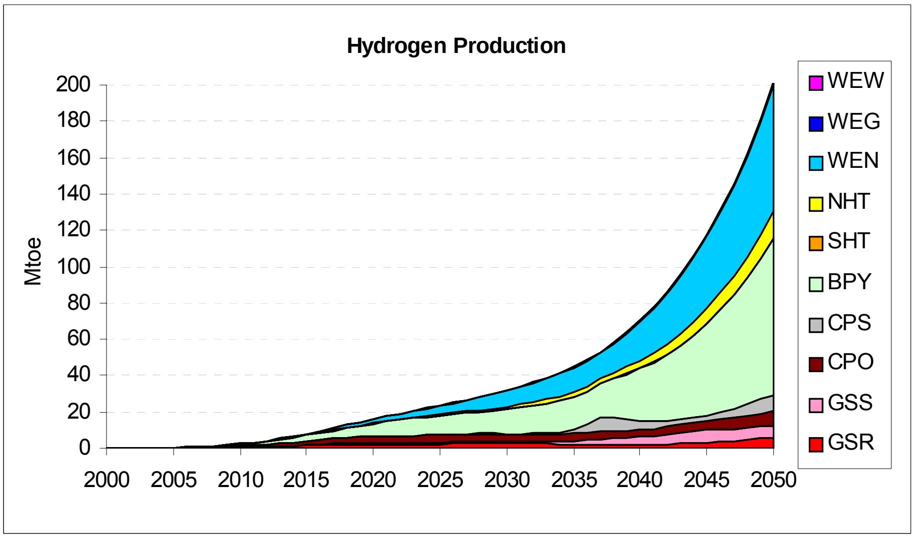
Electricity - World	**2001**	**2010**	**2020**	**2030**	**2050**
Electric capacity (GW)	3 375	4 667	6 347	8 752	15 117
Thermal, of which :	2 204	3 297	4 498	5 892	7 646
Coal, lignite	1 031	1 384	1 903	2 659	3 800
of which advanced coal	0	264	931	1 896	3 285
Gas	756	1 462	2 071	2 541	2 698
of which combined cycle	756	1 462	2 071	2 541	2 698
of which cogeneration (industry)	52	79	127	193	438
Oil	339	296	273	272	303
Biomass	26	76	124	227	407
Nuclear	355	396	500	811	1 765
of which new design	0	0	0	0	196
Hydro (large)	763	826	931	1 027	1 191
Hydro (small)	30	37	48	56	85
Wind	24	102	351	894	3 110
Solar	1	8	17	55	1 014
Electricity Production (TWh)	15 468	21 413	30 054	40 669	67 687
Thermal, of which :	10 074	14 894	21 744	28 125	38 509
Coal, lignite	5 848	6 571	10 334	14 500	22 539
of which advanced coal	0	1 771	6 012	10 910	19 976
Gas	2 934	6 936	9 650	11 202	12 477
of which combined cycle	944	4 475	6 575	7 352	5 677
of which cogeneration (industry)	250	380	612	930	2 111
Oil	1 136	931	1 009	1 049	1 035
Biomass	155	456	751	1 374	2 459
Nuclear	2 653	3 131	3 935	6 407	14 004
of which new design	0	0	0	0	1 635
Hydro (large)	2 703	3 185	3 640	4 054	4 829
Hydro (small)	90	109	143	168	253
Wind	37	195	713	1 950	7 544
Solar	1	7	16	80	1 559

Source: POLES model, SAPIENTIA-ref

5.5.2. Hydrogen production

The SAPIENTIA Reference scenario is not particularly intensive in hydrogen as the total production of hydrogen-energy only reaches 200 Mtoe in 2050, i.e. a figure that is only slightly superior to the current production of hydrogen-feedstock. Production in 2050 shows a mix that is dominated by the production of hydrogen from biomass pyrolysis, followed by electrolysis in dedicated nuclear power plants and hydrogen from fossil fuels, wit ha relatively balanced contribution of coal and gas, with and without CO_2 capture and Storage by the end of the period (Figure 5-17).

Figure 5-17: World hydrogen-energy production

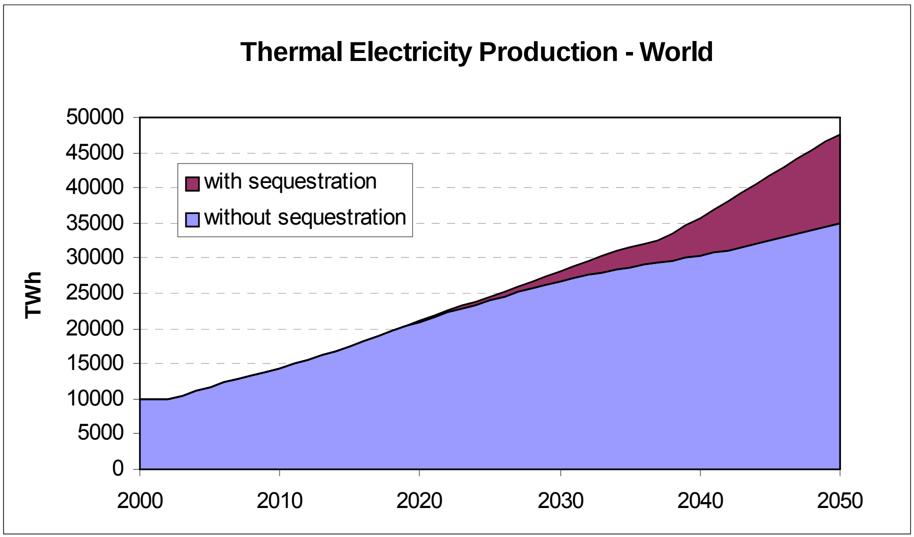


Source: POLES model, SAPIENTIA-ref

5.5.3. Carbon Capture and Sequestration

The development of CO_2 Capture and Storage begins by 2020 and increases rapidly from that date. In 2050 from the 48 000 TWh produced in thermal power plants, one fourth is produced with a CCS facility.

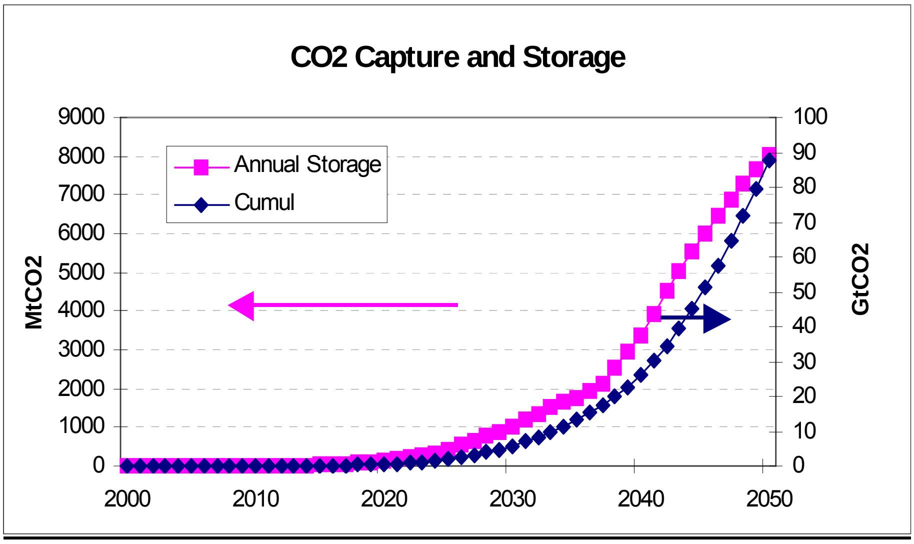
Figure 5-18: Thermal electricity production with and without sequestration



Source: POLES model, SAPIENTIA-ref

As a result, annual storage reaches 8 $GtCO_2$ in 2050, i.e. about one third of current total CO_2 emission level. Total cumulative CCS in 2050 corresponds to 90 $GtCO_2$ i.e. four times the current annual emissions (Figure 5-19). In the SAPIENTIA Reference case, CCS is far more than a marginal option in the world energy system.

Figure 5-19: World Carbon Capture and Storage annual and cumulative

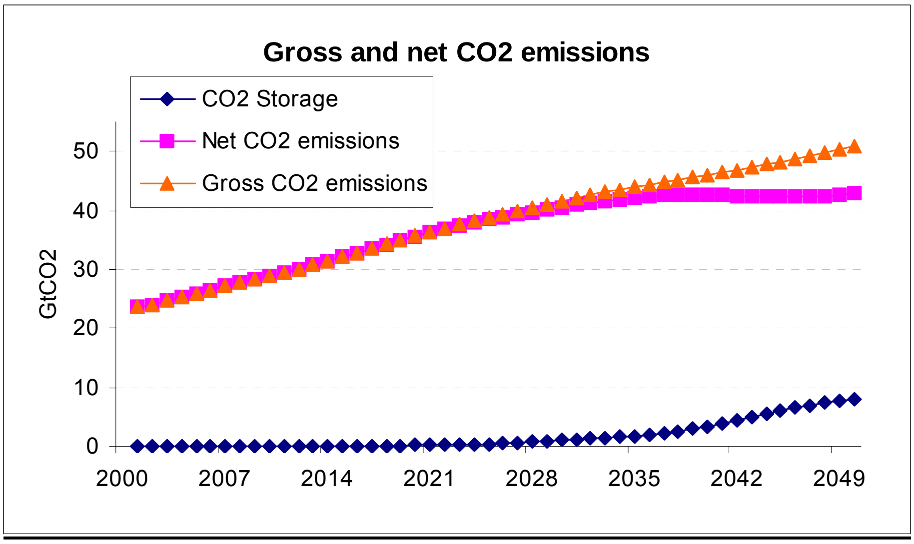


Source: POLES model, SAPIENTIA-ref

5.5.4. World CO_2 emissions

When the global CO_2 emission profile is considered, it appears that total net emissions of the energy sector are stabilised after 2040 in the Reference case. Indeed this scenario already includes significant carbon values in the different world regions. While total energy demand is limited by high primary energy prices and by the carbon value, emissions are further reduced by the increased contribution of non fossil fuels (renewables and nuclear) and finally by the contribution of CCS, which is quite significant as it brings the annual raw emissions of 50 $GtCO_2$ to net emissions of 42 $GtCO_2$ (Figure 5-20).

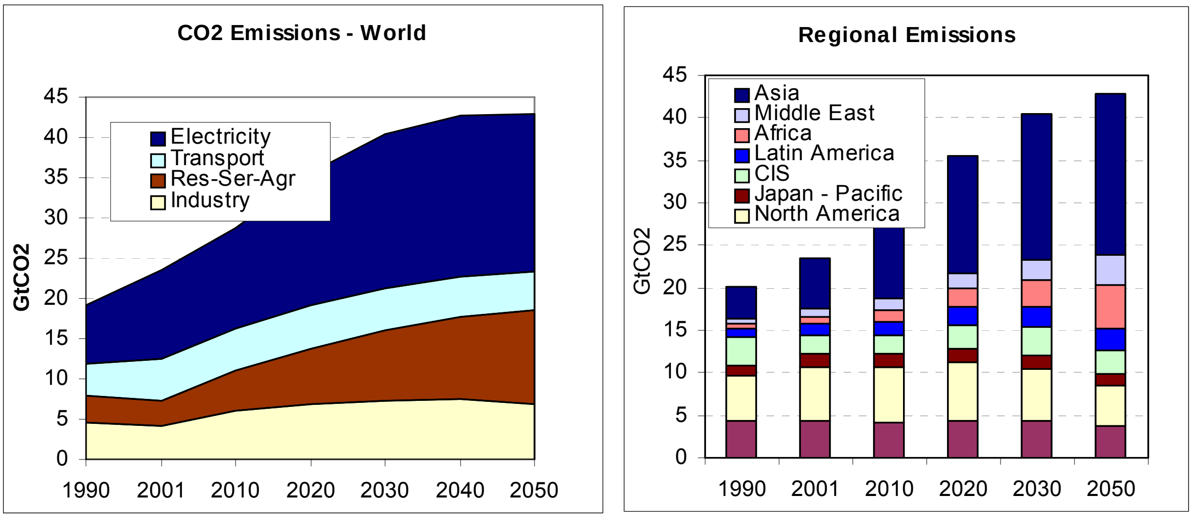
Figure 5-20: World gross and net (of CCS) CO_2 emissions



Source: POLES model, SAPIENTIA-ref

At the sector level power generation is by far the sector with the highest increase over the projection period, while the transport sector dynamics in consumption and emissions are strongly limited by oil price increases (Figure 5-21 left). In the regional perspective, it has to be noted that for Annex 1 regions the combination of high energy prices, structural factors and carbon values result in a stabilisation of emission by 2020, which is followed by a decrease in emissions to 2050: at that time horizon Annex 1 emission levels are lower than those of today (Figure 5-21 right). Consequently all the increment in CO_2 emissions come from the non-Annex 1 regions.

Figure 5-21: World CO_2 emissions by sector and region



Source: POLES model, SAPIENTIA-ref

The key factors in the development of the world electricity sector in the next decades are the growth differentials across world regions, the changes in primary energy supply and prices, the trends in technological developments. Indeed the development of electricity is impressive, however the structure of power generation is relatively stable in this Reference projection.

6. Stochastic Outlook Using PROMETHEUS

The main aim of the PROMETHEUS stochastic outlook is to:

- Provide assessments on the likelihood of key assumptions underpinning the Baseline. Such assessments provide insights on their status (for example the relative "optimism" or "pessimism" that characterises them). Such assessments can also take the form of joint probability analysis as for example an evaluation that a particularly favourable outcome occurs at the same time as another also favourable outcome.
- Provide assessments on ranges of key results thus giving indications as to the uncertainty associated with them. Unlike most ranges routinely reported in forecasting exercises PROMETHEUS assessments are characterised by a certain degree of rigour as they will have specific probabilities associated with them (quantiles).

6.1. Drivers and constraints to world development

This section performs a brief uncertainty analysis on the main drivers influencing world energy system development namely, population growth, economic activity, oil and gas reserves and climate policy.

6.1.1. Population trends

World population is expected to increase in the next 50 years (Table 6-1), but at lower rates compared to the period 1971-2000. It is unlikely to observe a higher average annual growth rate in 2000-2030 than the historical one in all regions.

Moreover, a deceleration in the period 2030-2050 is expected; the probability that world population will grow faster in that period compared to 2000-2030 is almost nil.

This deceleration which in PROMETHEUS analysis takes the form of low probabilities of attaining historical growth, is predicated on secular trends (evident over a number of years) suggesting an aging of the world population and a natural decline in fertility rates in the less developed regions.

---

[21] In PROMETHEUS the "Europe" region consists of EU-15 plus Norway and Switzerland. The "Rest of OECD" region consists of old members -> USA, Canada, Japan and Australia.

Table 6-1 Population growth summary statistics (all numbers are in %)

Population average annual growth rate 2000-2030				
	Europe [1]	Rest of OECD [1]	LDCs	World
Mean	0.08	0.66	1.06	0.97
Median	0.07	0.66	1.06	0.97
St.dev	0.08	0.04	0.05	0.05
Lower 5%	-0.04	0.60	0.97	0.90
Upper 5%	0.21	0.73	1.14	1.05
Historical growth 1971-2000	0.32	0.93	1.79	1.60
Probability to exceed historical	0.20	0.00	0.00	0.00

Population average annual growth rate 2000-2050				
	Europe	Rest of OECD	LDCs	World
Mean	-0.01	0.51	0.84	0.77
Median	-0.01	0.51	0.84	0.77
St.dev	0.09	0.05	0.06	0.06
Lower 5%	-0.16	0.44	0.73	0.67
Upper 5%	0.14	0.59	0.94	0.86

It should be noted that PROMETHEUS mean values for Europe are consistent with the UN constant fertility population projections. [22]

6.1.2. Economic activity

A slow decrease in the average annual growth rate of GDP per capita for the developed world, compared to the observed growth in 1971-2000, is expected. On the other hand in the Less Developed Countries a rapid increase is expected (Table 6-2).

The probability that the average annual growth rate in GDP per capita in the developed world for the period 2000-2030 will be higher than the historical observed is 7% (Europe 23.3%, Rest of OECD's ~5%).

Table 6-2: Summary statistics for the GDP per capita average annual growth rate in the PROMETHEUS' regions.

GDP per capita average annual growth rate (2000-2050) [%]				
	World	Europe	Rest of OECD	LDCs
Mean	2.68	1.61	1.81	3.41
Median	2.69	1.62	1.8	3.42
St. Dev	0.35	0.38	0.57	0.36
Lower 5%	2.09	0.96	0.87	2.81
Upper 5%	3.26	2.25	2.78	3.98
Historical growth 1971-2000	1.7	2.1	2.24	2.17
Probability to exceed historical (in period 2000-2030)	82.9	23.3	4.9	96.8

Figure 6-1 , presents the distributions of the ratios of GDP per capita in Europe and LDCs and the Rest of OECD respectively. The analysis suggests that LDCs are gradually converging to Europe but are unlikely to reach the European GDP per capita even in

---

[22] In the European environment outlook 4/2005 a growth rate of 0.09% pa for the period 2000-2030 is reported for EU-15, which almost corresponds exactly to PROMETHEUS mean.

2050. The probability that the GDP per capita in Europe would be more than 6.12 (the value for 2000) is only 0.7% implying a low probability of divergence. However, the probability that the GDP per capita in LDCs will be higher in 2050 than the GDP per capita in Europe in 2000 is 0%.

Comparing Europe with North America, Japan and Australasia, the probability that Europe will develop at a slower rate than these countries is 22.3%. On the other hand, there is also a 69% probability that the GDP per capita in Europe will still be lower than the average for these countries in 2050.

Figure 6-2 shows the cumulative distribution of the average annual growth rate of the GDP per capita in all three regions and in the world. Table 6-3 presents the summary statistics of the GDP average annual growth rate for 2000-2030 and 2000-2050 in the three regions.

These results are consistent with a general trend of diminishing marginal productivity of capital, labour and knowledge.

Figure 6-1 The distribution of the ratios of the GDP per capita in Europe and the other regions in 2050.

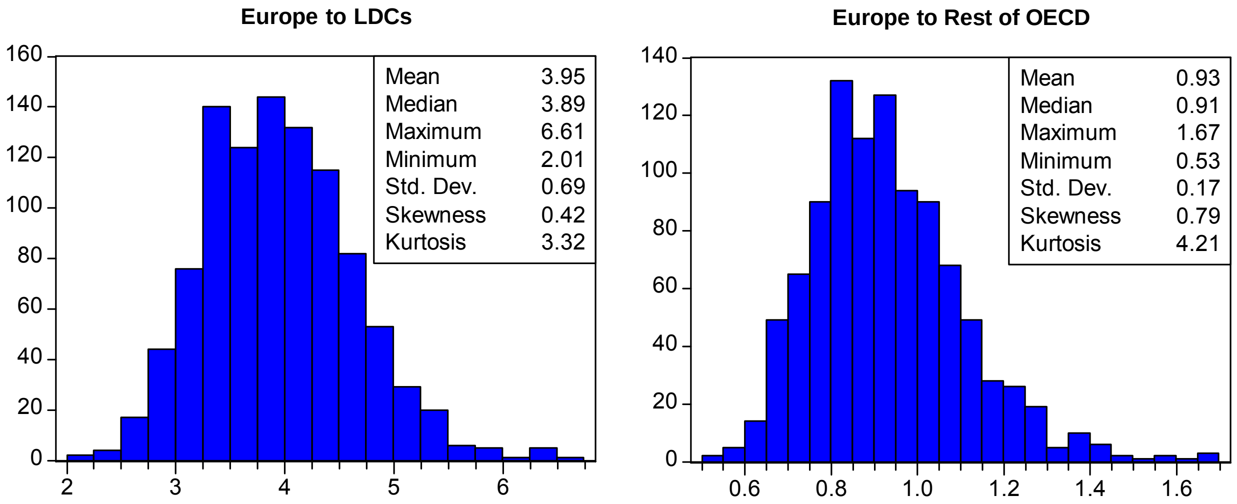


__Figure 6-2: Cumulative distribution of the GDP per capita average annual growth rate (2000-2050)__

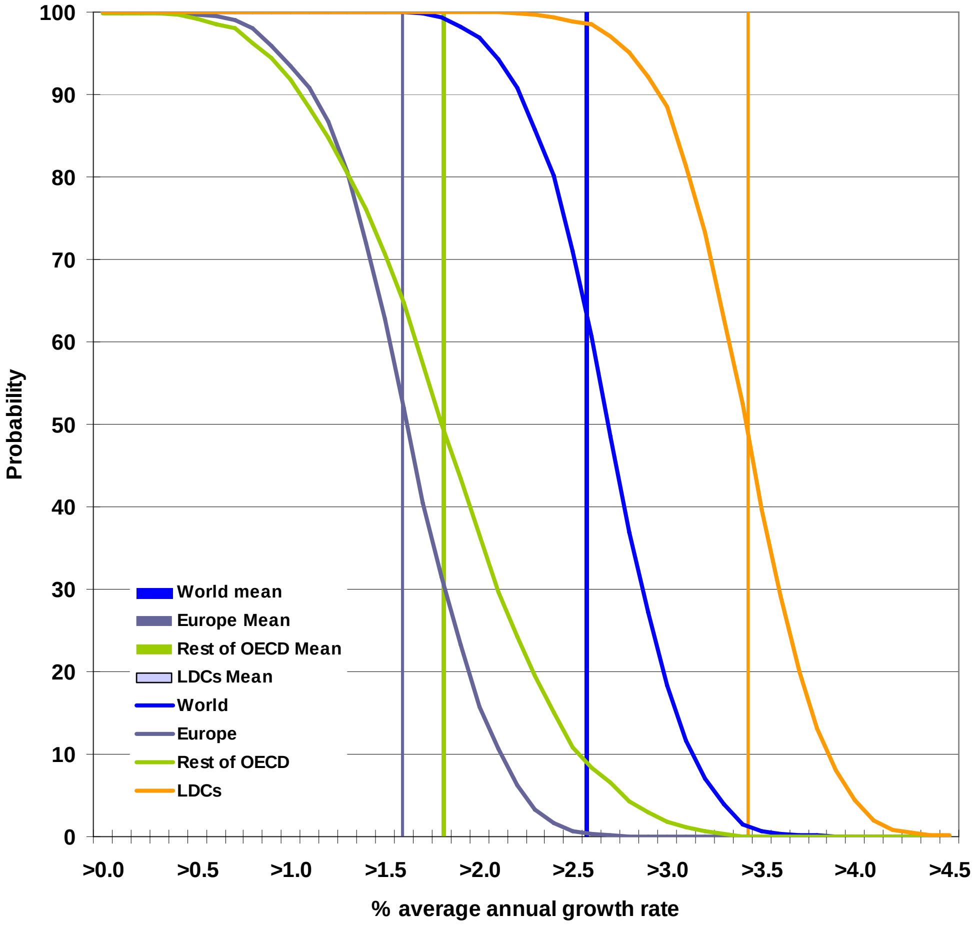


__Table 6-3: GDP average annual growth rate summary statistics__

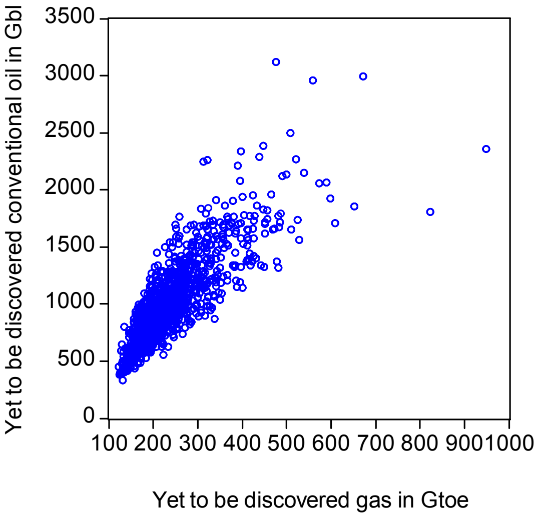
	GDP average annual growth rate (2000-2030) %			
	World	**Europe**	**Rest of OECD**	**LDCs**
Mean	3.02	1.90	2.02	3.94
Median	3.03	1.90	2.01	3.94
St. dev.	0.35	0.38	0.54	0.37
Lower 5%	2.43	1.25	1.15	3.32
Upper 5%	3.59	2.47	2.92	4.54

	GDP average annual growth rate (2000-2050) %			
	World	**Europe**	**Rest of OECD**	**LDCs**
Mean	2.68	1.61	1.81	3.41
Median	2.69	1.62	1.80	3.42
St. dev.	0.35	0.38	0.57	0.36
Lower 5%	2.09	0.96	0.87	2.81
Upper 5%	3.26	2.25	2.78	3.98

6.1.2.1. World oil and gas Reserves and supply

High uncertainty surrounds the amount of oil and gas that is yet to be discovered. This uncertainty has been incorporated into PROMETHEUS. Using studies conducted by USGS, stochastic analysis has been carried out in order to obtain distributions for the yet to be discovered oil and gas at the starting year of simulation. The two variables are jointly distributed i.e. there is a considerable amount of correlation between the unknown quantities of gas and oil due to geological factors (uncertainties on hydrocarbon formation and retention in sedimentary basis) (Figure 6-3). In each Monte Carlo experiment, PROMETHEUS begins from different world state regarding these variables. The rate of discovery as well as the rate of recovery is endogenous in PROMETHEUS depending on fuel prices and subject to their own specific uncertainties. For gas it is also assumed that often oil is sought and gas is found.

Figure 6-3 Scatter graph of the yet to be discovered gas and oil in the starting year of PROMETHEUS simulations



In 2001 the conventional oil R/P ratio was 47 years up from 21.9 in 1979. According to PROMETHEUS results the probability of exceeding the 1979 figure in 2050 is 95%, while the probability of exceeding the 2001 value is only 8.7%. Gas R/P ratios have been more or less steadily increasing in the last 30 years from around 35 to around 78 years. The probability of exceeding present R/P ratios in 2050 is only 5.2%. Figure 6-4 presents the distribution of conventional oil and gas reserves to production ratios in 2050.

Figure 6-4: Distribution of fossil fuels world reserves to production ratio in 2050

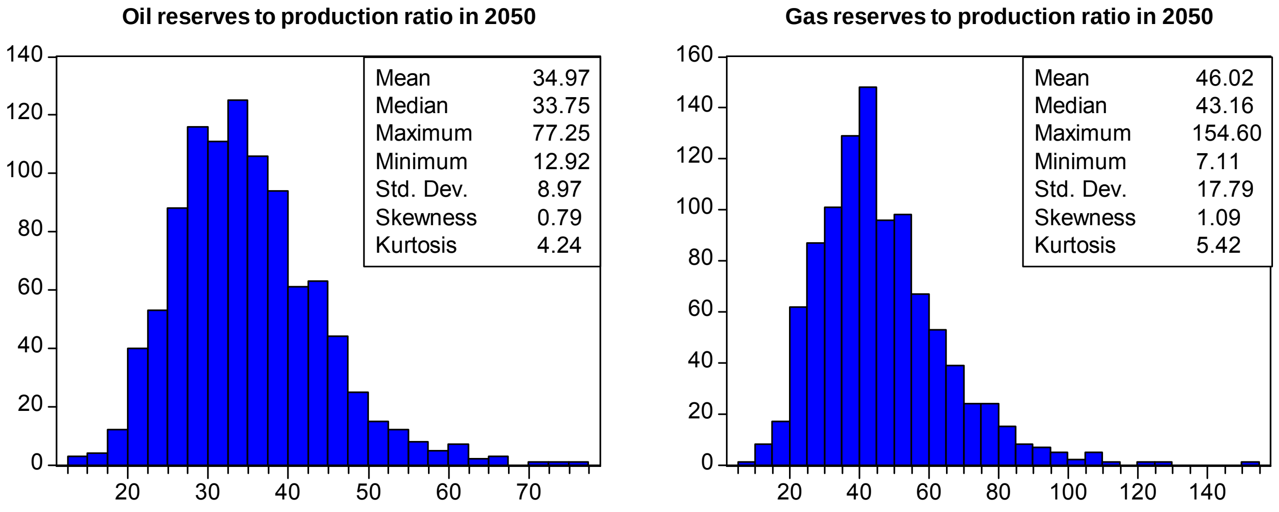


Table 6-4: Shares in oil production in 2050

Contribution in oil production in 2050 [%]		
	Conventional oil	Non - conventional oil
Mean	67.9	32.1
Median	73.7	26.3
St. Dev	15.6	15.6
Lower 5%	30.9	18.6
Upper 5%	81.4	69.1
in 2000	*99.5*	*0.5*

Non-conventional oil is expected to increase its share in the world oil production in 2050 as it compensates for the continuous decline in non-Gulf oil production (Table 6-4). There is a 5% probability that 69% of world oil production in 2050 comes from non-conventional oil. The importance of non-conventional oil raises issues related to CO_2 emitted during the recovery and processing of non-conventional oil, which are not taken into account by models.

6.1.2.2. International fuel prices

The PROMETHEUS baseline projects high oil and gas price means in 2050 (Table 6-5), 84€00/bl for oil and 554€00/toe for gas. Looking at the uncertainty in price evolution, by taking the ratios of the standard deviation to mean, it can be observed that in the more distant year the uncertainty is much higher. To aid the analysis, some probabilities for oil, gas and coal are given below, which are supplementary to lower and upper quantiles presented in the table:

- The probability that the oil price will exceed 100€00/bl in 2050 is 27.6%; the probability that the oil price will be less than today (the average oil price in 2005 is estimated at 45€00/bl) is 15.1%.
- The probability that the gas price will exceed the 735€00/toe (equivalent to 100€00/bl) is 21.6%; the probability to be lower than today (the average gas price in 2005 is estimated at 203€00/toe) is 5%
- The probability that the coal price will be higher than 70€00/tn is 21.9%. The probability that coal price will be lower than today (around 32.8€00/tn) is 19%

Figure 6-5 presents the distributions of oil to gas price ratio and the gas price to coal price ratio. According to distributions, the probability that the gas price is more expensive than oil in 2050 is 38%. Moreover, the probability that the oil price to gas price ratio will exceed the 2001 ratio is 50%. Regarding the gas price to coal price ratio the probability to exceed the 2001 ratio is 46.7%.

Deterministic analysis is ill suited to address directly security of supply issues and must resort to indirect measures such as import dependence and fuel diversification in order to assess security implications. It is clear however that a high import dependence does not necessary imply a deterioration in security since a lot will depend on the stability and reliability of the exporting region. Furthermore in a world of potentially abundant resources even dependence on insecure sources could represent a relatively minor risk if alternative and more secure sources can be activated within a reasonable time frame. Likewise poor fuel diversification does not always represent a security issue when it implies concentration on relatively secure alternatives. It is clear that the notion of risk (probability of damage) is central to security of supply considerations and the more directly it is addressed the more appropriate the analysis becomes.

PROMETHEUS is capable of carrying the analysis forward and addresses risk issues by providing analytical answers to questions of the type: what is the probability that dependence on an insecure source will exceed a given threshold at some point in the future? Or more appropriately: what is the probability that an imported fuel price or total fuel costs increase by more than an elevated (and damaging) rate in any three-year period?

PROMETHEUS is capable of addressing such questions by synthesising risks associated with World and regional fuel demand growth, geological uncertainties regarding the extent and geographical distribution of undiscovered resources (together with their interrelations) and the risk of supply disruptions expressed in terms of random reductions of productive capacity especially in the less stable regions of the World. Geological uncertainties are mostly measured using expert assessments and notably reports of the US Geological Survey. For risks disruptions of "political" nature historical evidence is used under the neutral assumption (which is not invalidated by statistical tests) that such risks have not exhibited statistically significant increases or diminutions over several decades.

The measure of security of supply presented here is the maximum increase in oil and gas price average in any 3-year period of the forecasting horizon (Figure 6-6). According to PROMETHEUS results, there is a 74% probability that the maximum oil and gas average price in any 3-year period in the next 50 years will be higher than the price increase observed in the oil crisis period 1978-81 (Iranian revolution and Iran-Iraq war); the price increase in that period was around 150€00/toe.

Table 6-5 Summary statistics for international fossil fuel prices for 2030 and 2050

€2000/toe

	2030			2050		
	Oil	**Gas**	**Coal**	**Oil**	**Gas**	**Coal**
Mean	396	283	61	615	554	82
Median	364	256	58	545	486	76
St. dev.	155	130	22	313	292	38
Lower 5%	206	127	34	246	203	35
Upper 5%	693	527	103	1197	1172	154

Figure 6-5 Ratios of oil to gas and gas to coal international prices in 2050

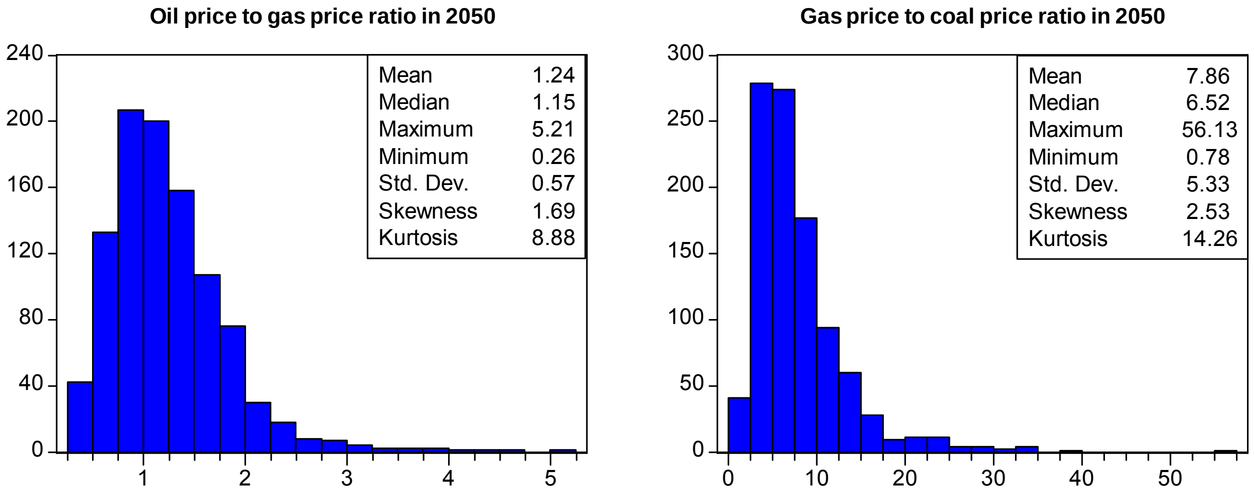
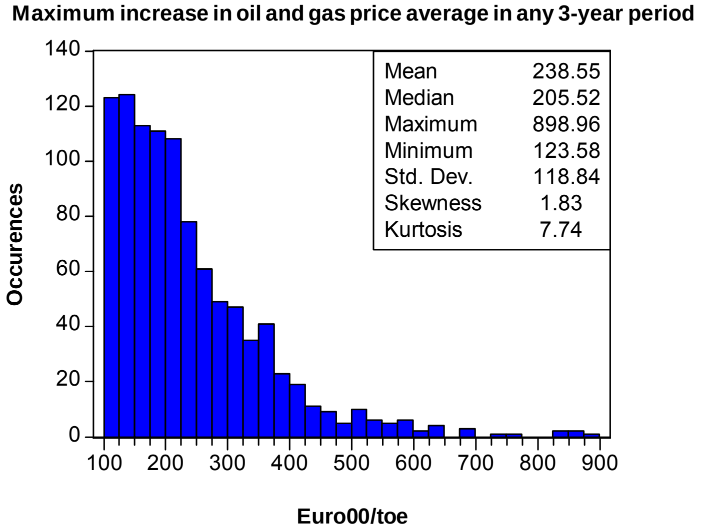


Figure 6-6: Distribution of maximum increase in oil and gas price average in any 3-year period between 2003-2050 in €00/toe



The above results indicate that there are significant probabilities to observe international fossil fuel prices that are considerably higher than the levels of today. Gas is expected to be an expensive fuel in the future and there is a considerable probability to be more expensive than oil. Sharp increases in oil and gas prices in any 3-year period are very likely to happen in the next 50 years and there is a noteworthy probability to be higher than in period '78-81.

6.1.2.3. Climate Policy

Assuming no policy response in the PROMETHEUS baseline would be equivalent to stating that there is no probability of such policy anywhere in the World for the next 50 years. Such an assumption alters the PROMETHEUS results from "maximum likelihood" to conditional distributions. The intensity of climate policy is endogenous in PROMETHEUS and is assumed to adapt albeit uncertainly and with considerable lags to climate change signals.

Since no truly scientific expertise regarding the timing, extent, nature and probability of climate policies is really available, it was decided to resort to a Delphi type methodology (among SAPIENTIA project partners) in order to derive the essential input. In terms of the methodology, the climate policy effort is measured through the introduction of an implicit carbon value (reflecting a carbon tax or the price of the permit in an emission quotas trading system) which instead of focusing on imposition of international targets and associated climate regime, concentrates on the impacts of emission reduction policies on technology development, independently of distributional impacts associated to target endowments. The alternative options, such as the introduction of a given emission profile at the regional or global level or the use of a GHG emission constraint would render model implementation much more complex and the policy definition highly dependent on the Baseline and its attributes. Assuming a target that is met would also violate the basic logic of PROMETHEUS, which must allow for failure to meet the given target.

The climate policy scenario adopted assumes that the EU leads the world climate abatement effort, followed by lesser efforts in other industrialized regions. Developing regions undertake abatement efforts only after industrialized regions do and their efforts are smaller or equal to those in industrialized regions.

Table 6-6 presents the summary statistics of the average carbon value in all regions for the periods 2000-2030 and 2000-2050. The average carbon value has been calculated by taking into account the effective carbon value in each region weighted by CO_2 emissions.

According to PROMETHEUS, the joint probability that LDCs and Rest of OECD will not exercise a climate policy in the whole period 2000-2050 is 5%.

Table 6-6 Summary statistics of the average carbon value in the three regions for the periods 2000-2030 and 2000-2050

Average carbon value for the period 2000-2030 in €2000/tn CO_2

	Europe	Rest of OECD	LDCs	World [1]
Mean	18.9	8.9	1.6	4.5
Median	17.3	6.4	0.0	3.4
Std. Dev	10.1	8.8	4.1	4.1
Lower 5%	5.2	0.0	0.0	0.7
Upper 5%	37.3	27.0	10.3	13.0

Average carbon value for the period 2000-2050 in €2000/tn CO_2

	Europe	Rest of OECD	LDCs	World [1]
Mean	31.1	19.9	8.0	11.5
Median	29.6	17.5	4.7	9.0
Std. Dev	15.1	13.5	9.1	8.7
Lower 5%	9.7	2.1	0.0	2.0
Upper 5%	57.9	44.9	26.5	29.1

[1] based on emissions weighted sum

6.1.3. Energy consumption

In the present section the emphasis is given on the probabilistic assessment of the main endogenous variables, which are grouped in terms of primary consumption, final consumption, and the technology outlook and climate implications.

6.1.3.1. Primary Consumption

Table 6-7 presents the summary statistics for the total primary consumption average annual growth rate in each region and in the world as a whole for the periods 2000-2030 and 2000-2050. It should be noted that traditional biomass consumption has not been taken into account in the calculation of total primary consumption. At the global level, the average annual growth rate of total primary consumption is expected to gradually slow down in the next 50 years. The historical observed average annual growth rate for the period 1971-2000 has 30% probability to be exceeded in the period 2000-2030.

In the developed world, there is small or zero probability that the average annual growth rate of total primary consumption will exceed the one observed in history (1971-2000). Although naturally energy consumption in LDCs grows on average much faster, a slowdown is also evident in this region since the probability to exceed their historical average annual growth rate is around 35%. These result from improvements in efficiency, continuing structural change and de-materialisation of production, the gradual introduction of effective climate policies (especially in Europe) and of course the slow down in economic growth which, as discussed in the previous section, is expected with particularly high probabilities

The different regional dynamics in primary consumption average annual growth rate result in a reduction of the share of the developed world in total primary consumption from its 2000 levels. Table 6-8 shows the summary statistics for the share of each region in world primary consumption. Although in 2000 the share of the developed world was higher than the LDCs (around 52%), in 2050 the probability that the developed world will still have the highest share is almost zero (in fact 0.1%). Moreover, the probability that the share of LDCs in total primary consumption will be higher than 2/3 is 88%, while the probability to be more than 3/4 is 35.5%. The above implies high probabilities of virtual LDCs dominance of the world energy system in 2050.

Table 6-9 presents the summary statistics of the average annual growth rate of energy intensity. In all regions improvement is expected and the probability that the energy intensity will deteriorate is assessed at zero. In Europe it is almost certain that the energy intensity in the first 30 years of the forecasting period will be improved with an average growth rate higher than the historically observed. Rest of OECD countries, however, have a probability of only 15% to exceed their historical observed average annual growth rate in the first 30 years of projection. In fact PROMETHEUS projects faster improvements in Europe compared to the rest of OECD (a reversal of trends observed in the period 1971-2000). The probability of Europe performing better than the Rest of OECD over the whole forecast period is estimated at 73.6%. The main reason for this reversal is the probability of a much higher climate policy intensity in Europe.

Table 6-7 Total primary consumption average annual growth rate summary statistics

Primary consumption annual average growth rate [%] for 2000-2030 and 2000-2050

	Europe		Rest of OECD		LDCs		World	
	2030	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
Mean	0.07	-0.09	0.59	0.24	3.03	2.31	1.94	1.48
Median	0.06	-0.10	0.55	0.18	3.02	2.28	1.93	1.47
St.dev	0.34	0.31	0.56	0.52	0.52	0.44	0.41	0.37
Lower 5%	-0.48	-0.58	-0.31	-0.52	2.20	1.61	1.29	0.89
Upper 5%	0.64	0.44	1.57	1.17	3.89	3.03	2.63	2.09
Historical growth 1971-2000	1.09	-	1.52	-	3.18	-	2.13	-
Probability to exceed historical	0.10	-	6.20	-	36.60	-	30.40	-

Table 6-8: Share of each region in total primary consumption in 2050

Share of each region in primary consumption in 2050 in %

	Europe	Rest of OECD	LDCs
Mean	7.7	19.4	72.8
Median	7.6	18.8	73.2
St.dev	1.4	4.4	5.3
Lower 5%	5.5	13.4	63.5
Upper 5%	10.3	27.7	80.6
Share in 2000	16.5	35.1	48.4
Probability to exceed historical	0.0	0.6	100.0

Table 6-9: Energy intensity average annual growth rate summary statistics

Average annual growth rate of energy intensity in 2000-2030 and 2000-2050 in %

	Europe		Rest of OECD		LDCs		World	
	2030	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
Mean	-1.8	-1.7	-1.4	-1.5	-0.9	-1.1	-1.1	-1.2
Median	-1.8	-1.7	-1.4	-1.6	-0.9	-1.1	-1.0	-1.2
St.dev	0.2	0.2	0.2	0.2	0.3	0.3	0.2	0.2
Lower 5%	-2.1	-2.0	-1.8	-1.9	-1.5	-1.6	-1.5	-1.6
Upper 5%	-1.4	-1.3	-1.0	-1.2	-0.3	-0.6	-0.7	-0.8
Historical growth 1971-2000	-1.3	-	-1.6	-	-0.9	-	-1.2	-
Prob. to be lower than historical	98.7	-	14.8	-	52.1	-	24.2	-

Finally, the median of energy intensity improvement average annual growth rate for LDCs for the period 2000-2030 is the same as the historical. This result can be explained by the growing importance of China and India, large regions with high energy intensity compared to other LDCs, within the group.

6.1.3.2. Primary consumption by energy source

Regarding the primary consumption per energy source at the world level, the following can be noted Table 6-10.

- Despite rising carbon values, coal consumption is expected to increase faster than oil and gas. This occurs in all regions except Europe, where the carbon values are on average high enough to prevent it. There are two reasons explaining this result. The first is the high oil and gas prices. The second is that China and India have large coal resources and according to PROMETHEUS results and in view of development requirements it is unlikely that they will desist from their exploitation in view of paucity of large scale alternative energy sources.

- Natural gas is less affected from carbon values in the first 30 years. But progressively gas is turned into an expensive energy form due to increasing scarcity resulting in higher prices, which leads to gradual decreases in consumption beyond 2030.

- In sharp contrast to the rapid increase in coal, oil consumption decreases in the developed countries. This is due to higher prices, as a result of the reduction in the non-Gulf conventional oil production and the penetration of the more expensive non-conventional oil, coupled with saturation effects in the transport sector (slow down in the increase of car ownership, lower utilisation rates and competition from non conventional transport modes). In the developing world there is a small increase resulting from large scale motorisation and despite loss of share of oil in non-transport sectors due to very high prices.

Table 6-10: Primary consumption per energy source summary statistics

Average annual growth rate of primary consumption per energy form in Europe								
	2000 - 2030				2000 - 2050			
	Coal	**Oil**	**Gas**	**Other[1]**	**Coal**	**Oil**	**Gas**	**Other[1]**
Mean	0.09	-0.63	0.18	1.00	0.17	-0.76	-0.62	0.99
Median	0.07	-0.63	0.17	0.93	0.22	-0.77	-0.64	0.96
St.dev	1.01	0.34	0.43	0.69	0.73	0.32	0.38	0.55
Lower 5%	-1.54	-1.20	-0.50	-0.04	-1.06	-1.29	-1.19	0.15
Upper 5%	1.74	-0.07	0.91	2.33	1.32	-0.22	0.02	1.92
Historical growth 1971-2000	-1.24	-0.04	4.96	6.84	-	-	-	-
Probability to exceed historical	90.30	4.00	0.00	0.00	-	-	-	-

Average annual growth rate of primary consumption per energy form in Rest of OECD								
	2000 - 2030				2000 - 2050			
	Coal	**Oil**	**Gas**	**Other[1]**	**Coal**	**Oil**	**Gas**	**Other[1]**
Mean	0.81	-0.22	0.33	1.91	0.10	-0.44	-0.38	1.96
Median	0.89	-0.22	0.28	1.81	0.16	-0.44	-0.43	1.90
St.dev	1.42	0.54	0.84	1.29	1.01	0.53	0.67	0.72
Lower 5%	-1.78	-1.12	-0.98	0.02	-1.66	-1.29	-1.37	0.91
Upper 5%	3.04	0.66	1.79	4.25	1.65	0.46	0.83	3.26
Historical growth 1971-2000	2.40	0.81	0.85	6.55	-	-	-	-
Probability to exceed historical	12.10	2.40	24.60	0.00	-	-	-	-

Average annual growth rate of primary consumption per energy form in LDCs								
	2000 - 2030				2000 - 2050			
	Coal	**Oil**	**Gas**	**Other[1]**	**Coal**	**Oil**	**Gas**	**Other[1]**
Mean	3.44	1.94	2.67	4.51	2.44	1.37	1.76	4.38
Median	3.49	1.93	2.61	4.74	2.55	1.37	1.74	4.62
St.dev	1.19	0.62	1.10	2.64	0.95	0.46	0.65	1.53
Lower 5%	1.54	0.90	0.95	0.14	0.67	0.60	0.70	1.53
Upper 5%	5.22	2.96	4.66	8.60	3.86	2.13	2.86	6.56
Historical growth 1971-2000	2.31	2.89	4.72	7.32	-	-	-	-
Probability to exceed historical	85.40	6.00	4.50	16.00	-	-	-	-

Average annual growth rate of primary consumption per energy form in World								
	2000 - 2030				2000 - 2050			
	Coal	**Oil**	**Gas**	**Other[1]**	**Coal**	**Oil**	**Gas**	**Other[1]**
Mean	2.62	0.90	1.70	2.82	1.83	0.57	0.96	2.89
Median	2.63	0.91	1.65	2.79	1.91	0.57	0.92	2.94
St.dev	1.04	0.45	0.81	1.61	0.83	0.35	0.50	1.02
Lower 5%	0.93	0.11	0.45	0.31	0.35	0.00	0.20	1.13
Upper 5%	4.19	1.64	3.18	5.54	3.07	1.14	1.85	4.46
Historical growth 1971-2000	1.79	1.39	2.89	6.84	-	-	-	-
Probability to exceed historical	79.40	12.70	8.20	0.20	-	-	-	-

[1] **Including Nuclear, renewable electricity and modern biofuels**

6.1.3.3. Final Consumption

Industry

In Table 6-11 the summary statistics of the average annual growth rate of final consumption in industry are presented. In the calculation of total final consumption, biomass (modern and traditional) has been excluded.

In developed countries it is expected that the final consumption in industry will be reduced in the next 50 years, due to continuing de-industrialisation, continuing improvements in efficiency and de-materialisation of industrial production. However, there is a probability of 25% in Europe and 40% in the Rest of OECD countries that the average annual growth rate of final consumption in industry will be positive. These probabilities relate to situations in which high GDP average growth rates are observed (higher than the median of the distribution). In the Less Developed Countries the median of the growth in final industrial consumption for the period 2000-2050 is 1.95%, while the probability to exceed 3% is 8%.

Electricity plays an important role in industrial final consumption for the next 50 years. In all regions electricity consumption is expected to increase from its current levels, but the probabilities to exceed the historical observed average annual growth rate is 3% in Europe, 8% in the Rest of OECD countries and 26% in the LDCs. However, there are cases in which electricity consumption decreases; the probability of lower electricity consumption than in 2000 is 6% for Europe, 5% for the Rest of OECD and 1% for LDCs. These are situations of low economic growth with high fossil fuel prices because of limited resources.

Coal consumption in developed countries is expected to decrease, especially in Europe due to secular trends away from coal but also to ever intensifying climate policies. However, there is 19% probability in Europe and 36% probability in the Rest of OECD countries that coal actually grows in industry as result of high oil and gas prices. In LDCs, on the other hand, coal consumption in industry is surrounded by considerable uncertainty reflected in the standard deviation of 1.6%pa. This is mostly due to uncertainties surrounding the path and structure of industrial energy demand in China and India.

Oil consumption is also expected to decrease in developed countries. There is however a 13.3% probability in Europe and 25.4% in the Rest of OECD countries that oil consumption will grow (high economic growth cases). In LDCs, however, there is high uncertainty on the penetration of oil in industry which is related to the uncertainty in oil price. However, oil will not be a leading option for industrial consumption in LDCs.

As regards the natural gas consumption, in Europe there is 0% probability to exceed the historical (1971-2000) growth rate. This is due to the fact that natural gas in Europe currently has such a large share in non-electric industrial consumption that it is constrained to follow the fate of such consumption, which as mentioned earlier has a high probability of declining. Moreover, the probability to observe an increase in gas consumption from its current levels is only 1.2%.Finally, the probability to observe the historical growth rate of the period 1971-2000 in the Rest of OECD is 18% and 52% in LDCs.

Table 6-11: Industry final consumption summary statistics (excluding, steam, hydrogen and biomass/waste)

Final consumption in Industry average annual growth rate in % - Europe

	2000 - 2030					2000 - 2050				
	Total	**Coal**	**Oil**	**Gas**	**Elec.**	**Total**	**Coal**	**Oil**	**Gas**	**Elec.**
Mean	-0.25	-1.61	-0.91	-0.68	1.14	-0.39	-1.30	-1.04	-1.17	0.81
Median	-0.23	-1.59	-0.85	-0.71	1.13	-0.37	-1.31	-1.00	-1.18	0.82
St.dev	0.58	1.51	0.97	0.57	0.53	0.58	1.47	0.98	0.52	0.53
Lower 5%	-1.27	-4.27	-2.55	-1.60	0.29	-1.39	-3.88	-2.72	-2.02	-0.05
Upper 5%	0.67	0.79	0.60	0.32	1.97	0.54	1.04	0.49	-0.30	1.67
Historical growth 1971-2000	-0.06	-2.44	-1.36	3.48	2.08	-	-	-	-	-
Probability to exceed historical	37.90	71.90	67.90	0.00	3.30	-	-	-	-	-

Final consumption in Industry average annual growth rate in % - Rest of OECD

	2000 - 2030					2000 - 2050				
	Total	**Coal**	**Oil**	**Gas**	**Elec.**	**Total**	**Coal**	**Oil**	**Gas**	**Elec.**
Mean	-0.08	-0.51	-0.50	-1.49	1.35	-0.17	-0.89	-0.76	-1.53	1.00
Median	-0.13	-0.54	-0.48	-1.58	1.37	-0.25	-0.82	-0.71	-1.50	0.99
St.dev	1.04	2.32	1.10	1.97	0.70	1.00	2.42	1.13	1.99	0.63
Lower 5%	-1.71	-4.36	-2.37	-4.72	0.10	-1.67	-4.93	-2.65	-4.79	-0.01
Upper 5%	1.81	3.39	1.29	1.80	2.47	1.63	2.91	1.05	1.83	2.03
Historical growth 1971-2000	0.39	-1.11	0.22	0.29	2.28	-	-	-	-	-
Probability to exceed historical	30.90	60.70	23.90	18.20	8.20	-	-	-	-	-

Final consumption in Industry average annual growth rate in % - LDCs

	2000 - 2030					2000 - 2050				
	Total	**Coal**	**Oil**	**Gas**	**Elec.**	**Total**	**Coal**	**Oil**	**Gas**	**Elec.**
Mean	2.95	3.07	1.92	2.63	3.60	1.97	1.83	0.84	1.44	2.87
Median	2.97	3.37	1.93	2.58	3.56	1.95	2.02	0.85	1.42	2.86
St.dev	0.81	1.84	1.45	1.03	0.70	0.75	1.78	1.20	0.83	0.61
Lower 5%	1.54	-0.60	-0.43	0.98	2.44	0.81	-1.47	-1.06	0.15	1.90
Upper 5%	4.25	5.46	4.31	4.38	4.77	3.25	4.36	2.88	2.83	3.91
Historical growth 1971-2000	3.34	4.18	2.81	2.52	4.03	-	-	-	-	-
Probability to exceed historical	31.20	28.30	26.70	52.40	26.20	-	-	-	-	-

Final consumption in Industry average annual growth rate in % - World

	2000 - 2030					2000 - 2050				
	Total	**Coal**	**Oil**	**Gas**	**Elec.**	**Total**	**Coal**	**Oil**	**Gas**	**Elec.**
Mean	1.89	2.57	0.95	1.14	2.57	1.28	1.58	0.27	0.48	2.09
Median	1.90	2.83	0.89	1.11	2.55	1.26	1.71	0.26	0.45	2.08
St.dev	0.68	1.59	1.08	0.91	0.50	0.66	1.57	0.94	0.80	0.47
Lower 5%	0.72	-0.54	-0.78	-0.27	1.77	0.23	-1.23	-1.28	-0.76	1.33
Upper 5%	3.01	4.76	2.76	2.62	3.42	2.40	3.92	1.90	1.79	2.89
Historical growth 1971-2000	1.56	1.70	0.83	1.65	2.94	-	-	-	-	-
Probability to exceed historical	69.30	75.00	51.90	28.50	22.80	-	-	-	-	-

Residential – Services – Agriculture

In Table 6-12 the summary statistics of the final consumption in residential, services and agriculture sectors are presented. In the calculation of final consumption modern and traditional biomass has not been taken into account. The table shows that in Europe a reduction in the total final consumption from its current levels is expected while in the rest of the World the consumption increases. Europe has zero probability to exceed its historical growth rate, while for the Rest of OECD it is around 34% and for LDCs it is more than 95%. The zero probability in Europe is due mostly to saturation effects in heating.

Coal consumption in LDCs is expected to increase with 75% probability in the period 2000-2030 and 60% probability in 2000-2050. This is mostly due to the increasing weight of China in the region and difficulties in supplying demand for heat in these countries from alternative sources.

Gas is considered as a mid-term option in all regions. In the last 20 years of the projection, gas is affected by high prices on average. In the whole forecasting period up to 2050, gas consumption is expected to decrease in Europe and in the rest of OECD countries from its 2000 levels with probabilities 99.5% and 70% which are very close to the probabilities estimated in the case of oil. In LDCs gas is expected to increase with probability of 84%.

Electricity is and is expected to remain a dynamic part within the residential and services final consumption. In all regions the average annual growth rate of electricity is expected to be positive with 92% probability in the Rest of OECD and 97% in Europe. In LDCs the mean increase is 3.8%/yr, while the probably to exceed 5%/yr is 5%. In developed regions it is almost completely unlikely that the historical growth in residential electricity continuous for the next 30 years. On the other hand for LDCs PROMETHEUS suggests that there is a 6.3% probability of faster growth.

Table 6-12: Final consumption in Residential, Services and Agriculture summary statistics (excluding hydrogen and renewable energy sources consumption)

Final consumption in Residential-Services-Agriculture average annual growth rate in % - Europe

	2000 - 2030					2000 - 2050				
	Total	**Coal**	**Oil**	**Gas**	**Elec.**	**Total**	**Coal**	**Oil**	**Gas**	**Elec.**
Mean	-0.09	-3.48	-1.42	-0.25	0.86	-0.29	-3.11	-1.39	-0.95	0.73
Median	-0.10	-3.57	-1.38	-0.23	0.86	-0.29	-3.10	-1.36	-0.94	0.73
St.dev	0.30	1.86	0.68	0.46	0.43	0.27	1.72	0.60	0.39	0.39
Lower 5%	-0.58	-6.42	-2.60	-1.03	0.14	-0.71	-5.80	-2.48	-1.57	0.11
Upper 5%	0.42	-0.43	-0.36	0.51	1.57	0.16	-0.23	-0.45	-0.31	1.40
Historical growth 1971-2000	1.28	-8.35	-0.56	5.14	3.66	-	-	-	-	-
Probability to exceed historical	0.00	99.70	11.00	0.00	0.00	-	-	-	-	-

Final consumption in Residential-Services-Agriculture average annual growth rate in % - Rest of OECD

	2000 - 2030					2000 - 2050				
	Total	**Coal**	**Oil**	**Gas**	**Elec.**	**Total**	**Coal**	**Oil**	**Gas**	**Elec.**
Mean	0.78	-1.64	-0.22	0.25	1.46	0.32	-1.70	-0.32	-0.37	0.90
Median	0.76	-1.67	-0.22	0.24	1.46	0.33	-1.78	-0.32	-0.37	0.90
St.dev	0.55	1.66	0.75	0.78	0.63	0.53	1.50	0.62	0.68	0.63
Lower 5%	-0.12	-4.37	-1.42	-0.99	0.44	-0.55	-4.14	-1.34	-1.45	-0.12
Upper 5%	1.72	1.17	1.00	1.57	2.51	1.22	0.74	0.69	0.74	1.97
Historical growth 1971-2000	0.99	-5.18	-1.29	0.65	3.92	-	-	-	-	-
Probability to exceed historical	33.80	98.10	92.00	29.90	0.00	-	-	-	-	-

Final consumption in Residential-Services-Agriculture average annual growth rate in % - LDCs

	2000 - 2030					2000 - 2050				
	Total	**Coal**	**Oil**	**Gas**	**Elec.**	**Total**	**Coal**	**Oil**	**Gas**	**Elec.**
Mean	2.87	1.59	1.60	1.83	4.37	2.58	0.34	1.55	1.16	3.80
Median	2.87	1.98	1.68	1.90	4.33	2.56	0.80	1.71	1.26	3.80
St.dev	0.61	2.80	1.10	1.28	0.90	0.54	3.19	1.11	1.30	0.74
Lower 5%	1.89	-3.32	-0.36	-0.38	2.86	1.72	-5.90	-0.62	-1.19	2.57
Upper 5%	3.86	5.48	3.24	3.85	5.84	3.46	4.61	3.05	3.00	5.00
Historical growth 1971-2000	1.87	-2.66	2.41	6.15	5.74	-	-	-	-	-
Probability to exceed historical	95.40	92.90	23.50	0.00	6.30	-	-	-	-	-

Final consumption in Residential-Services-Agriculture average annual growth rate in % - World

	2000 - 2030					2000 - 2050				
	Total	**Coal**	**Oil**	**Gas**	**Elec.**	**Total**	**Coal**	**Oil**	**Gas**	**Elec.**
Mean	1.75	1.48	0.76	0.84	2.75	1.56	0.37	0.84	0.30	2.44
Median	1.74	1.81	0.79	0.83	2.73	1.55	0.72	0.92	0.28	2.43
St.dev	0.43	2.66	0.73	0.65	0.60	0.42	2.92	0.77	0.68	0.57
Lower 5%	1.04	-3.29	-0.47	-0.22	1.78	0.87	-5.14	-0.62	-0.83	1.47
Upper 5%	2.46	5.27	1.94	1.95	3.76	2.27	4.48	1.99	1.46	3.40
Historical growth 1971-2000	1.40	-3.30	0.37	2.69	4.41	-	-	-	-	-
Probability to exceed historical	78.40	95.00	70.40	0.20	0.20	-	-	-	-	-

6.1.4. Technology outlook

PROMETHEUS contains considerable technological detail for the road transport, the power generation and the hydrogen production sectors.

6.1.4.1. Transport sector

Table 6-13 presents the summary statistics for the activity and the final consumption in the transport sector. At the global level, there is a 97% probability that transport activity per capita will increase between 2000 and 2050. In addition, there is also 97% probability that the oil consumption will also increase in the same period. The 3% probability of reduction (both in activity and in oil consumption) is related to very low economic growth cases. Moreover, electricity and hydrogen start gaining share in the world transport consumption after 2030 particularly in the developed world, where the consumer oil price is higher than in the developing countries.

In Europe, saturation effects in human mobility are likely to be experienced since there is 53% probability that the transport activity per capita (passenger cars) will be lower in 2050 than its current levels. There is also 87% probability that the oil consumption will be decreased in the long run due to the car efficiency improvement and the penetration of the more efficient (in terms of oil consumption) hybrid car. Electricity, hydrogen and gas (through fuel cells) are also expected to increase their share in total consumption in the long run, while in the medium term (until 2030) the probability to exceed their historical growth is 51%.

In the Rest of OECD countries, saturation effects in transport activity per capita have been already observed and the probability that the transport activity per capita will be lower than in 2000 is 60%. Oil consumption is also expected to be reduced, for the same reasons mentioned in Europe, with a probability of 73%; this is lower probability than Europe due to the fact that consumer oil prices in Rest of OECD are, in principle, much lower than Europe making then new technologies (such as hybrid) not so competitive to the conventional car.

In the Less Developed Countries there are no saturation effects. It is certain with 100% probability that the transport activity per capita will increase from its current levels, as result of the economic transformation that is taking place. Transport activity growth will be based on oil consumption (the probability that the oil consumption will be increased in the next 50 years is 99.9%).

In LDCs there is high uncertainty regarding the new energy forms (electricity, gas and hydrogen). The uncertainty is higher than in the developed world (as it can be seen by the standard deviation to mean ratios of the average annual growth rate distributions in the three regions). The new fuels benefit mainly in high economic growth and high oil price scenarios.

Table 6-13: Transport sector activity and final energy consumption summary statistics

Transport sector indicators - Average annual growth rate 2000 - 2030 [%]												
	Europe			Rest of OECD			LDCs			World		
	Activity	Consumption		Activity	Consumption		Activity	Consumption		Activity	Consumption	
	km per capita	Oil	Other fuels	km per capita	Oil	Other fuels	km per capita	Oil	Other fuels	km per capita	Oil	Other fuels
Mean	0.08	-0.18	0.15	-0.02	-0.02	2.84	2.43	2.61	-2.42	0.63	1.18	-0.28
Median	0.08	-0.19	0.31	-0.01	-0.01	3.15	2.41	2.69	-2.24	0.63	1.23	-0.11
Std. Dev	0.41	0.42	2.85	0.50	0.54	3.72	0.45	0.66	4.55	0.30	0.45	3.46
Lower 5%	-0.59	-0.86	-4.57	-0.82	-0.95	-3.43	1.70	1.50	-10.04	0.13	0.40	-5.93
Upper 5%	0.76	0.51	4.66	0.78	0.86	8.54	3.22	3.51	5.30	1.12	1.84	5.51
Historical (1971 - 2000)	-	2.77	0.24	-	1.93	0.71	-	3.68	-2.51	-	3.68	-2.51
Probability to be higher than historical	-	0.00	51.00	-	0.00	68.50	-	2.40	51.60	-	0.00	72.10

Transport sector indicators - Average annual growth rate 2000 - 2050 [%]												
	Europe			Rest of OECD			LDCs			World		
	Activity	Consumption		Activity	Consumption		Activity	Consumption		Activity	Consumption	
	km per capita	Oil	Other fuels	km per capita	Oil	Other fuels	km per capita	Oil	Other fuels	km per capita	Oil	Other fuels
Mean	-0.03	-0.40	2.53	-0.12	-0.28	4.52	1.89	1.81	1.46	0.52	0.76	2.55
Median	-0.02	-0.39	2.60	-0.11	-0.25	4.63	1.89	1.84	1.55	0.52	0.77	2.65
Std. Dev	0.36	0.37	1.72	0.46	0.50	2.19	0.39	0.52	2.69	0.28	0.38	2.09
Lower 5%	-0.61	-0.99	-0.40	-0.84	-1.12	0.74	1.22	0.94	-3.29	0.06	0.11	-1.08
Upper 5%	0.56	0.21	5.26	0.63	0.56	7.97	2.55	2.62	5.70	0.99	1.39	5.86

Figure 6-7, presents the cumulative distribution of the cost per vehicle-km of non-conventional cars relative to gasoline otto engine cars in Europe in 2050. The figure on the right relates to the fuel cell cars, while the left shows the rest of the non-conventional car options included in PROMETHEUS namely, hybrid cars, pure electric cars and H_2 internal combustion engine cars.

Hybrid cars have the highest probability to be the cheapest option in 2050 for the European consumer (69.8%), followed by diesel cars (21.7%) and H_2 internal combustion engine cars (2.4%).

The probability that hybrid cars will be cheaper than conventional gasoline cars in terms of cost per km is more than 92%. Electric cars have a probability of 17% and H_2 internal combustion engine cars 14%.

Fuel cells have only 1.2% (hydrogen fuel cells) and 0.8% (gas fuel cells) probabilities to be cheaper than conventional gasoline cars in 2050. The probability that the cost of the hydrogen fuel cells will be less than double the cost of the conventional car is 55%, while the same probability for the gas fuel cells (with reformer) is 47%.

Hydrogen fuel cells have 97% probability to be cheaper than gas fuel cells in 2050. In general, gas fuel cells with reformers can not be considered as a long term option, but only as short term alternative until hydrogen fuel cells dominate the market.

Among the hydrogen-based technologies, the H_2 internal combustion engine car appears to represent a stop gap solution, before fuel cells becomes sufficiently attractive after 2030, and, therefore, its long-term prospects are not expected to be significant.

Fuel cells have high risks and high prospects. They can completely be out of the market or fully dominate it (minimum 0%, maximum 93% of new registrations in Europe in 2050). According to PROMETHEUS results, the penetration of fuel cells in the transport market is constrained by the high cost of the fuel cell stack itself and not by the cost of hydrogen. The above results suggest that the penetration of hydrogen in transport depends mainly on the penetration of the fuel cells and not on the penetration of the H_2 internal combustion engine car.

Figure 6-8 shows the share of non conventional cars in the total passenger car stock in 2050 at the global level. The probability to have more non-conventional than conventional cars in 2050 is 46.5%; the probability for their share to be less than 15% is 5% and the probability to be higher than 85% is also 5%. The distribution has multiple modes (at least three are visible in the figure), which correspond broadly with possible breakthroughs in different non-conventional options.

Figure 6-7: Cumulative distribution of the relative to otto engine cost per km (Europe, 2050)

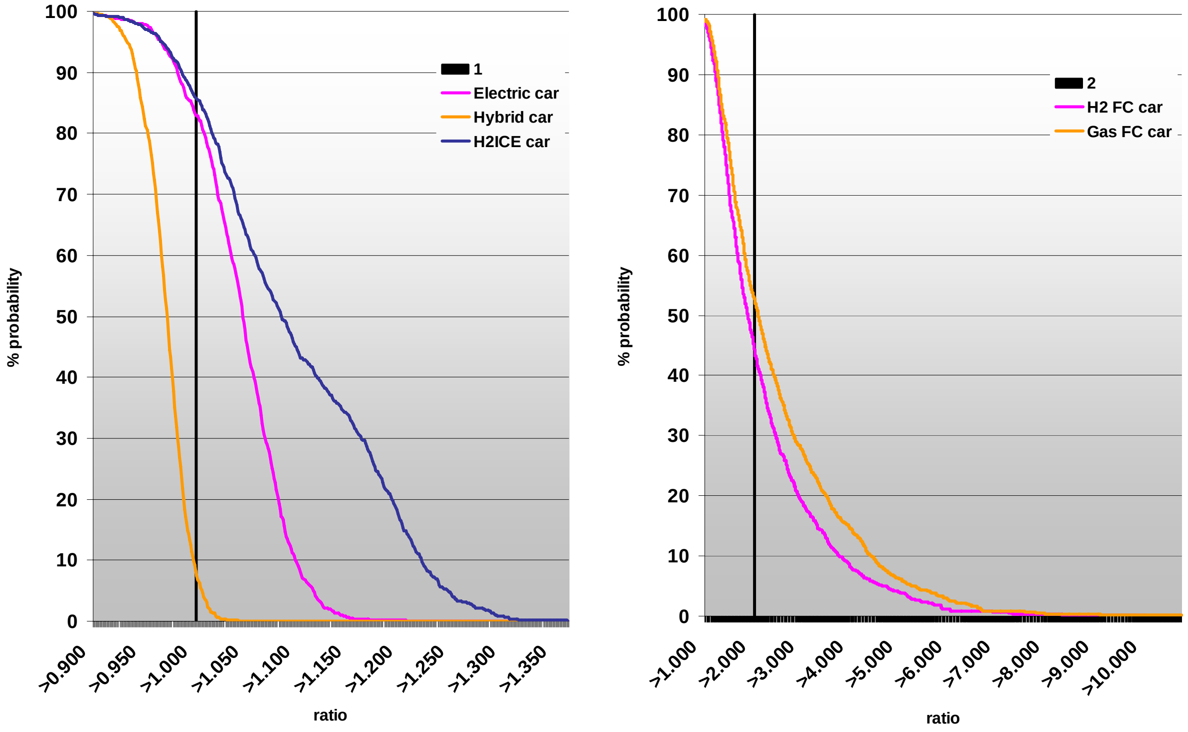
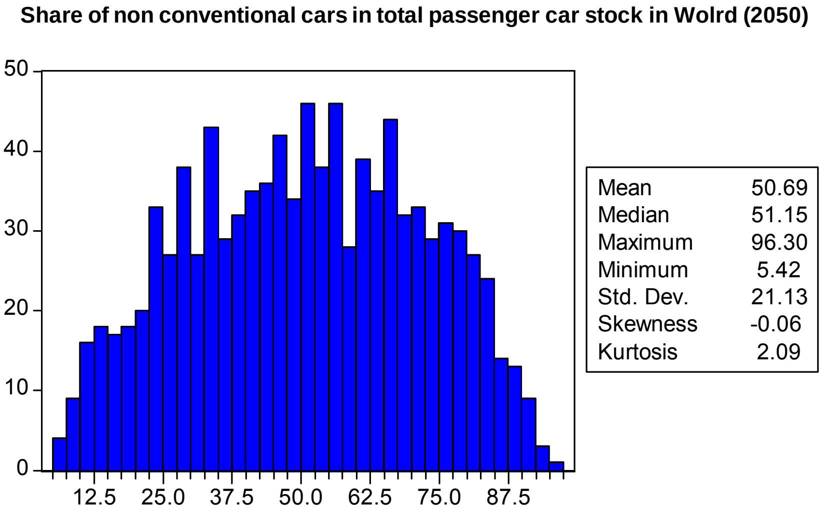


Figure 6-8: Distribution of the share of non conventional cars in world total passenger car stock in 2050.



6.1.4.2. Power generation sector

Figure 6-9 presents the cumulative distribution of the ratios of the electricity generation costs for selected technologies to the Gas Turbine Combined Cycle production cost, which is currently the dominant choice for new medium load generation capacity in the world. The technologies considered are the Integrated Coal Gasification, the Biomass Gasification with combined cycle, the Wind Offshore and the New Nuclear (4th generation).

Wind offshore has the highest probability to be cheaper than Gas Turbine Combined Cycle, followed by New Nuclear, Biomass Gasification and Coal Gasification. Before analysing the results, some key probabilities regarding the production cost of each technology are given:

- The probability that Biomass Gasification will be cheaper than Gas Turbine Combined Cycle in 2050 is 97.2%; the same probability in 2025 is 60%.
- The probability that Integrated Coal Gasification will be cheaper than Gas Turbine Combined Cycle is 80.2%; the same probability in 2025 is 53.6%.
- The probability that New Nuclear will be cheaper than Gas Turbine Combined Cycle in 2050 is 98.1%; the same probability in 2025 is 2.8%.
- The probability that Wind Offshore will be cheaper than Gas Turbine Combined Cycle in 2050 is 98.4%; the same probability in 2025 is 73.1%.

The above results indicate that the current dominance of Gas Turbine Combined Cycles is unlikely to extend beyond the medium term when the likelihood of high gas prices increases and many competing options have a good change of being attracted.

Integrated Coal Gasification prospects are affected by possible high carbon values, but the probability that generation from this option will be cheaper than Gas Turbine Cycle in 2050 is higher than in 2025.

New Nuclear remains an expensive option until 2030. The low probability to be cheaper than Gas Turbine Combine Cycle in 2025 and the corresponding high probability in 2050 indicates that the cost prospects of 4th generation nuclear improve dramatically towards the end of the forecast horizon.

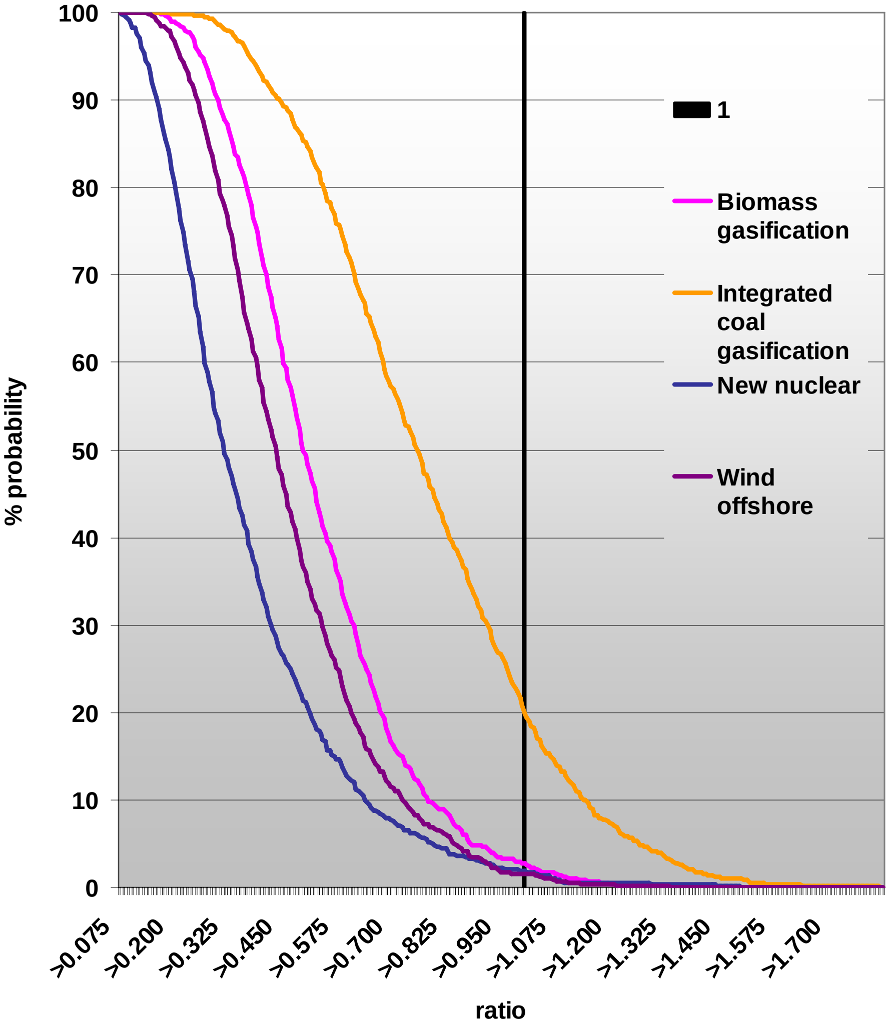
Biomass Gasification has 70.3% probability to be cheaper than Gas Turbine Combined Cycle when the effective carbon tax is higher than 20€00/tn CO_2.

Finally, the Wind Offshore technology shows 98.4% probability in 2050 to be cheaper than Gas Turbine Combined Cycle in terms of production cost. On the other hand it is well understood that this option is subject to limited potential (depending on very shallow waters at favourable distances from the shore).

Table 6-14 shows the summary statistics of the share of selected technologies in the electricity production in 2030 and 2050 in Europe.

Hydro potential in Europe is nearly exhausted and hence this option is expected to lose share in electricity production in the next 50 years; the probability that in 2030 its share will be higher than it was in 2000 is only 15.3%; the same probability in 2050 is 12.5%. The probability that its share will be higher in 2050 than 2030 is 10%.

<u>Figure 6-9: Cumulative distribution of the production cost per KWh in 2050 (Europe) for selected technologies; costs are relative to Gas Turbine Combined Cycle</u>



The share of renewable electricity production is expected to be close to the share of nuclear electricity production (in 2030 the means are 17% and 21% respectively, while in 2050 renewable electricity has a slightly higher mean than nuclear electricity - 24.4% and 22.6%). In fact, the probability that the share of renewable electricity will be higher than the share of nuclear electricity in 2050 is 61.1%. Among the renewable technologies the probability that wind will have the highest share in 2050 is 61.5%. The probability that wind offshore production will be higher than wind onshore in 2050 is 30% (in 2030 it is only 3%). This result suggests that wind offshore will not come into the electricity production until the combination of the following occurs: wind onshore cost reduction, effective climate policy and high gas prices.

Gas Turbine Combined Cycle gains share until 2030, where the probability to exceed its 2000 share is 95.7%, but in the longer term it loses share in favour of renewable, nuclear, clean coal, supercritical coal and CO_2 capture and storage technologies. Supercritical coal and Integrated Coal Gasification increase their share until 2030, but afterwards there is 51% probability for Supercritical and 48.7% probability for Integrated Coal Gasification to have lower share in 2050 than in 2030; CO_2 capture technologies benefit from the share reduction of clean coal and supercritical technologies.

Table 6-14: Share in electricity production in 2030 and in 2050 summary statistics for Europe

Share in electricity production in 2030 (Europe)

	Hydro	Wind	Solar	Biomass Gasification	Biomass Thermal	Renewable (excl. hydro)	Nuclear	Carbon Capture and Seq.	Clean Coal	Super critical coal	Gas turbine combined cycle
Mean	14.97	10.86	0.43	2.22	3.43	16.93	20.97	3.12	6.97	8.99	14.97
Median	14.16	9.67	0.23	1.75	2.97	16.33	18.29	2.20	5.32	6.72	13.87
St.dev	3.91	6.13	0.59	1.69	1.66	6.37	7.30	2.86	5.39	7.37	4.90
Lower 5%	10.66	2.96	0.05	0.49	1.85	7.53	13.49	0.34	1.31	1.84	9.12
Upper 5%	22.39	22.73	1.50	5.46	6.75	29.04	35.70	8.99	18.26	24.26	24.37
Share in 2000	17.96	0.81	0.00	0.13	2.00	2.93	32.01	0.00	0.00	0.00	8.98
Probability to exceed 2000	15.30	100.00	100.00	99.90	90.10	100.00	9.80	100.00	100.00	100.00	95.70

Share in electricity production in 2050 (Europe)

	Hydro	Wind	Solar	Biomass Gasification	Biomass Thermal	Renewable (excl. hydro)	Nuclear	Carbon Capture and Seq.	Clean Coal	Super critical coal	Gas turbine combined cycle
Mean	13.26	13.86	4.78	2.75	3.00	24.39	22.59	6.72	7.18	9.05	7.78
Median	12.14	12.72	3.65	2.20	2.59	23.83	19.75	5.42	5.59	6.97	7.65
St.dev	4.84	7.52	3.96	2.05	1.49	8.36	10.64	5.18	5.82	7.60	1.64
Lower 5%	8.10	4.00	0.75	0.66	1.56	12.00	10.33	0.90	1.04	1.59	5.43
Upper 5%	22.47	28.06	13.21	6.58	5.75	39.12	43.47	16.76	19.79	25.17	10.46
Share in 2000	17.96	0.81	0.00	0.13	2.00	2.93	32.01	0.00	0.00	0.00	8.98
Probability to exceed 2000	12.50	100.00	100.00	100.00	77.80	100.00	17.80	100.00	100.00	100.00	20.10

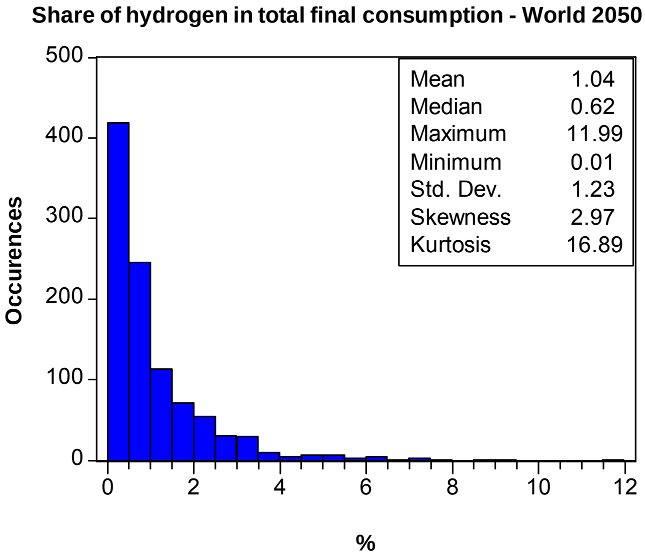
The CO_2 capture technologies benefit only in situations where high carbon values are introduced. There is 12% probability that the CO_2 capture technologies have lower share in 2050 than in 2030. There is high uncertainty in CO_2 capture technologies stemming from the uncertainty surrounding an effective climate policy.

Finally there is high uncertainty concerning nuclear electricity production. In the medium term there is 10% probability that the nuclear share will be higher in 2050 than in 2000, which reflects the current prospects for restricting nuclear expansion in Europe and the United States. However, in the longer term, where intensive climate policies are likely to occur in combination with high fossil fuel prices, the probability that nuclear increases its share in 2050 from 2000 levels is 17.8%.

6.1.4.3. Hydrogen sector

The PROMETHEUS baseline scenario does not incorporate on average major and worldwide policy initiatives to favour hydrogen as a fuel. The expected hydrogen demand in 2050 is 120Mtoe with a standard deviation of 161Mtoe at the global level. This reflects the high uncertainty in the penetration of hydrogen in demand sectors, which results from high uncertainty concerning the ultimate reduction in the cost of fuel cells. The expected share of hydrogen in final consumption is 1.04%, while the probability that hydrogen consumption will account for more than 5% in total final energy demand is only 2%.

Figure 6-10: Distribution of hydrogen share in total final consumption in 2050 (World)



Hydrogen is more likely to be produced by renewable and nuclear technologies. Electrolysis (nuclear, wind and directly from grid) does not appear as a likely option for large scale production. On the other hand the analysis suggests key competition between renewable and fossil fuel technologies (the likelihood of the one or the other depending to a large extent on carbon value uncertainty) and between nuclear and renewable technologies (where the likelihood depends on uncertainty concerning breakthroughs on nuclear or alternatively a more decentralised power generation structure). (Table 6-15).

Table 6-15: Hydrogen production at global level in 2050 summary statistics

Share in hydrogen production in 2050 - World

	Fossil fuels	Renewable	Nuclear	Electrolysis	Carbon Capture and Seq.
Mean	27.79	32.56	21.12	9.40	9.12
Median	21.40	24.32	10.23	2.42	3.05
St.dev	24.88	28.97	24.98	15.68	13.84
Lower 5%	0.50	0.69	0.14	0.03	0.06
Upper 5%	77.24	90.33	77.42	48.91	40.86

6.1.5. Climate change

6.1.5.1. Greenhouse gas emissions

Regarding energy related CO_2 emissions, the probability to exceed the historical average annual growth rate is 0.1% in Europe, 5.3% in the Rest of OECD countries and 81.4% in LDCs. At the global level, the probability to exceed the historical average annual growth rate is 63.3% reflecting the projected dominance of LDCs in global emissions (Table 6-16).

Moreover, in the developed world the higher likelihood of a strong climate policy, the reduction of energy demand, the increased contribution of non-fossil fuels (renewable and nuclear) technologies in the power generation and the penetration of CO_2 capture and storage technologies as result of effective climate policy mean that the probability of actually observing a reduction in CO_2 emissions over the whole horizon is around 75%. On the other hand for LDCs the probability of such an occurrence is virtually non-existent.

Table 6-16: Energy related CO_2 emissions summary statistics

Energy related CO_2 emissions average annual growth rate %								
	Europe		**Rest of OECD**		**LDCs**		**World**	
	00-30	**00-50**	**00-30**	**00-50**	**00-30**	**00-50**	**00-30**	**00-50**
Mean	-0.30	-0.58	0.29	-0.25	2.86	1.99	1.83	1.20
Median	-0.31	-0.57	0.29	-0.27	2.87	2.02	1.85	1.22
St.dev	0.40	0.37	0.73	0.63	0.65	0.54	0.53	0.46
Lower 5%	-0.96	-1.23	-0.89	-1.24	1.77	1.08	0.94	0.46
Upper 5%	0.36	0.03	1.49	0.83	3.97	2.85	2.73	1.92
Historical growth 1971-2000	1.06	-	1.44	-	2.28	-	1.67	-
Probability to exceed historical	0.10	-	5.30	-	81.40	-	63.30	-

Table 6-17: Non energy related GHG emissions summary statistics

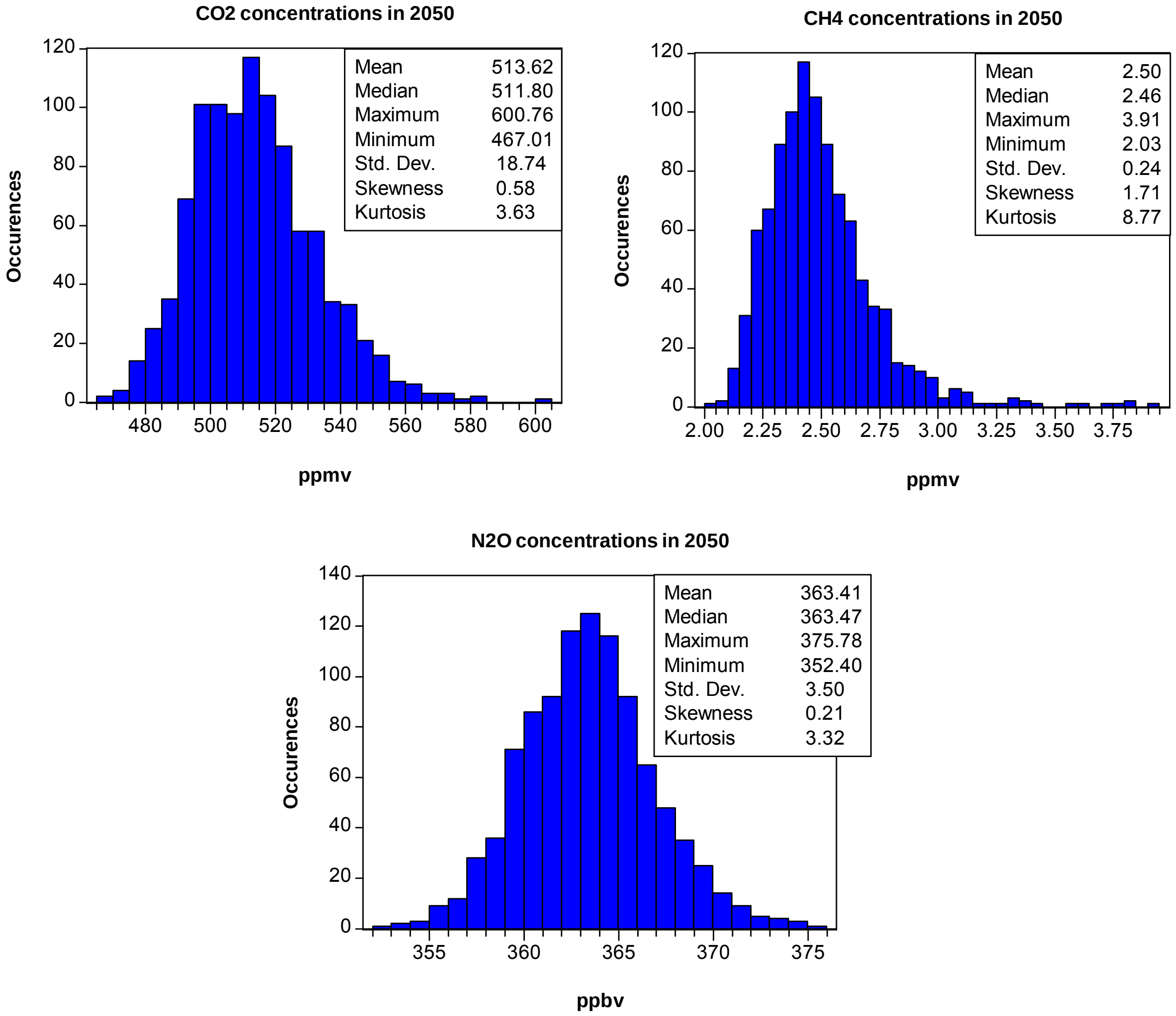
Non energy related GHG average annual growth rate % - World						
	CO_2		**CH_4**		**N_2O**	
	00-30	**00-50**	**00-30**	**00-50**	**00-30**	**00-50**
Mean	0.64	0.64	1.12	0.96	0.68	0.53
Median	0.63	0.63	1.10	0.90	0.69	0.53
St.dev	0.60	0.51	0.28	0.34	0.26	0.26
Lower 5%	-0.34	-0.18	0.70	0.53	0.26	0.10
Upper 5%	1.63	1.48	1.62	1.60	1.08	0.93
Historical growth 1971-2000	3.37	-	1.27	-	2.03	-
Probability to exceed historical	0.00	-	26.80	-	0.00	-

For non-energy related GHG emissions PROMETHEUS does not incorporate marginal abatement cost curves. On the other hand the key GHGs (in terms of the contribution to climate change) are incorporated and uncertainties, associated with the drivers and the contribution to the climate change problem, have been taken into account. It is in this context that the probabilities referred to in the subsequent paragraphs must be interpreted. The probability to exceed the historical average annual growth is zero for non-energy CO_2 and N_2O and 26.8% for CH_4. However, the probability that the non-energy related GHG emissions will increase from their 2000 levels is 90.1% for non-energy CO_2, 100% for CH_4 and 98% for N_2O Table 6-17). In view of the absence of marginal abatement cost curves mechanisms in PROMETHEUS these probabilities must be considered as exaggerated.

6.1.5.2. Greenhouse Gas Concentrations

The distribution of the GHGs atmospheric concentrations in 2050 are shown in Figure 6-11.

Figure 6-11: Distribution of GHGs atmospheric concentrations in 2050



6.1.5.3. Temperature change

In order to calibrate the equations calculating the temperature change in PROMETHEUS, the Transient Climate Response (TCR) methodology, described in IPCC Third Assessment Report has been used. The TCR is defined as the globally averaged surface air temperature change at the time of CO_2 concentrations doubling in 1%/yr CO_2 concentrations increase. It includes all GHGs. According to this methodology the runs start at 2000 and the CO_2 concentration doubling occurs in 2070. The advantage of the methodology is that it uses the same forcing for all models and thus it is useful for calibrating the model response. The mean of the temperature change equation in PROMETHEUS was calibrated in order to reproduce the mode of the results from 19 models participating in this exercise in IPCC TAR.

Figure 6-12 presents the distribution of the temperature change from its 2000 levels in 2065. PROMETHEUS considers a 15 years commitment period in temperature change, thus in order to observe the temperature change due to 2050 greenhouse gases concentrations the climate module is run forward to 2065. The mean projected temperature change in 2065 from 2000 levels is +1.02°C and the standard deviation is 0.36°C. According to PROMETHEUS the probability of a temperature increase of more than 2°C from pre-industrial levels is 22.1%.

Figure 6-13 shows the distribution of the highest temperature increase in any one decade of the forecasting period. It also shows the end year of the decade in which the highest temperature increase occurs. Studies (for example “Climate Protection Strategies for the 21st Century. Kyoto and Beyond, WBGU, Berlin, 2003”.) have suggested an increase of 0.2^{o}C in a decade as a threshold for damage to ecosystems (difficulties in adaptation). According to PROMETHEUS, the probability to observe an increase of more than 0.2^{o}C is 91%. Furthermore, the probability of more than 0.3^{o}C is 46.6%. There is 40% probability that the decade where the maximum increase in temperature occurs will end between 2040 and 2050. On the other hand there is still a 14.3% probability that it may end before 2020.

Figure 6-12: Distribution of temperature change in 2065 from its 2000 levels

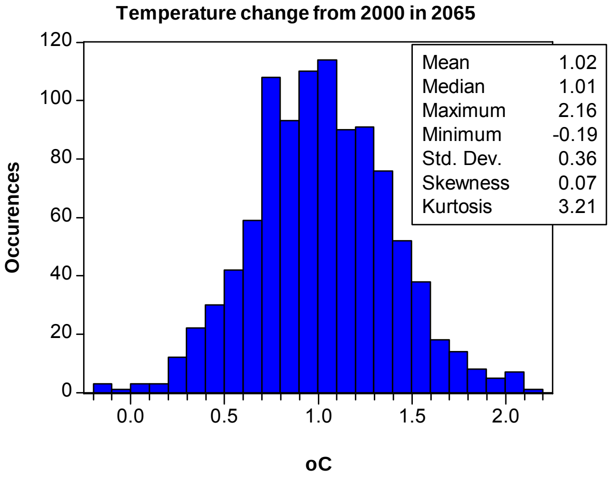
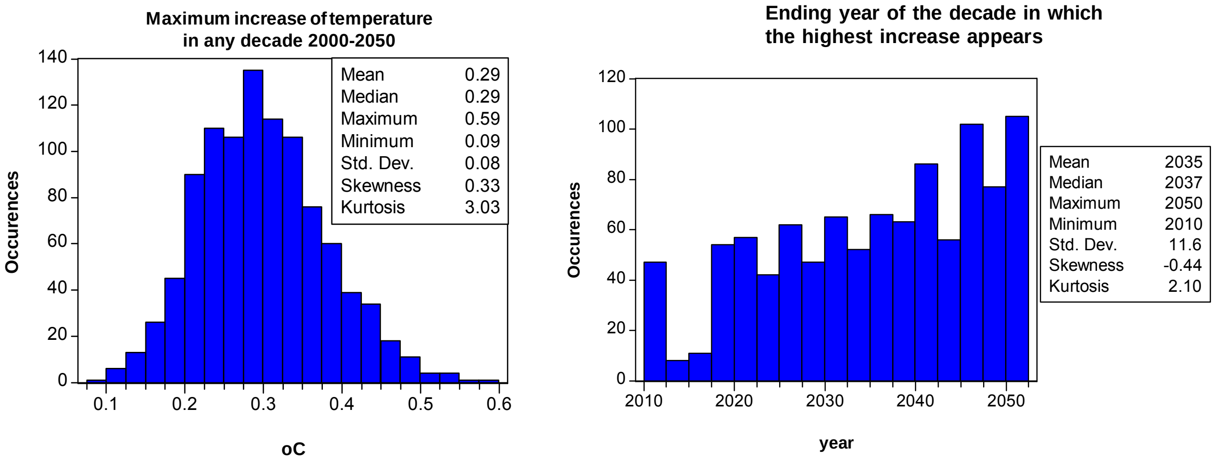


Figure 6-13: Distribution of the maximum increase over a decade and distribution of the ending year of the decade in which the maximum increase occurs



6.1.6. General remarks on PROMETHEUS stochastic outlook

Table 6-18 gives correlation coefficients between some key/indicative variables of the outlook. Such tables provide a concise picture of interrelations between variables. However, they must be read with caution since the correlation gives no indication of the direction causality. The latter can have a very complex structure requiring the consideration of many correlations simultaneously.

Looking at the first column of the table reveals a key feature of the outlook. PROMETHEUS results suggest that uncertainty concerning the future energy system lies mostly along an axis dominated by economic activity.

High growth in world economic activity is associated with:

- Fast fossil fuel resource depletion resulting in slower reserves addition tighter fuel supply and ultimately high or even very high international fuel prices.
- Higher emissions of CO_2 and other GHGs leading to high concentrations and increasing the risk of damaging climate change.
- High R&D investments both because of the higher availability of funds generated from the higher activity levels but also as result of the urgency created by the higher fossil fuel prices.
- Extensive technological innovation arising both from learning from research but also through the accumulation of experience as the capital stock is turned over faster, new technologies replacing more traditional one.

The combination of the last two points imply a higher likelihood of low capital costs and high variable costs for energy transformation and use, which lead to increased capital intensity and radical change in the energy system. Clearly, the opposite picture is more likely to emerge in cases of lower growth giving lower prices and emissions, weaker R&D investments, less innovation and a more static energy system.

A major conclusion from the above is that uncertainty is driven by demand in a resource constraint world where both demand and supply are relatively price inelastic.

This has important implications for strategies aimed at increased sustainability, especially with regard to environmental damage. There seems to be little likelihood of some of the “virtuous cycle” scenarios that seem to be so popular in perspective analysis. Such scenarios usually describe a rapidly changing energy system both in terms of technological innovation and economic and social structure combined with improved environmental performance but without involving lower economic activity and resource restrictions thus maintaining a reasonable cost of energy services. The major policy challenge is to define a strategy that raises the likelihood of such occurrences from the presently very low levels.

Table 6-18: Correlation matrix of a subset of PROMETHEUS variables denoting the dominance of the economic activity; Bold figures mark correlations greater than 0.4; red highlights significant negative correlations

	World GDP av. annual growth rate	**Av. oil int. price**	**Av. gas int. price**	**Av. carbon value**	**Cum. CO2 emiss.**	**Elec. final cons. in 2050**	**Other final cons. in 2050**	**Transp. activity in 2050**	**REN share in elec. prod. in 2050**	**H2 dem. in 2050**	**Non conv. Veh. share in 2050**	**Non conv. oil prod. in 2050**	**Cum. R&D in 2050**	**Biomass gassif. capital cost in 2050**	**Integr. Coal Gasif. capital cost in 2050**	**De-central. PV capital cost in 2050**
Average oil int. price	**0.58**															
Average gas int. price	**0.47**	**0.75**														
Average effective carbon value	0.07	0.04	0.04													
Cumulative CO2 emissions	**0.54**	**0.41**	0.27	-0.12												
Electricity final consumption in 2050	**0.77**	**0.47**	**0.42**	0.00	**0.57**											
Other final consumption in 2050	**0.60**	**0.45**	0.35	-0.22	**0.45**	**0.43**										
Transport activity in 2050	**0.59**	0.30	0.21	-0.15	0.37	**0.46**	**0.40**									
Renewable share in elec. prod in 2050	0.08	0.12	0.21	0.13	-0.02	0.02	0.04	0.00								
Hydrogen demand in 2050	0.29	0.20	0.26	0.07	0.17	0.25	0.23	0.19	0.01							
Non conventional vehicles share in 2050	0.15	-0.11	-0.01	-0.01	0.05	0.16	0.10	0.19	-0.04	0.27						
Non conventional oil production in 2050	**0.44**	**0.77**	**0.51**	0.03	0.32	0.36	0.34	0.19	0.03	0.15	-0.10					
Cumulative R&D expenditure in 2050	**0.75**	**0.82**	**0.80**	0.17	0.34	**0.59**	**0.48**	0.39	0.18	0.30	0.03	**0.61**				
Biomass gassification capital cost in 2050	**-0.74**	**-0.83**	**-0.84**	-0.18	-0.35	**-0.60**	**-0.46**	-0.38	-0.21	-0.28	0.01	**-0.59**	**-0.96**			
Integrated Coal Gasificiation capital cost in 2050	**-0.65**	**-0.67**	**-0.64**	-0.04	**-0.45**	**-0.56**	-0.39	-0.35	-0.07	-0.26	-0.04	**-0.47**	**-0.75**	**0.78**		
Decentralised PV capital cost in 2050	**-0.45**	**-0.48**	**-0.53**	-0.11	-0.22	-0.35	-0.30	-0.25	-0.18	-0.19	-0.02	-0.31	**-0.58**	**0.61**	**0.48**	
New nuclear capital cost in 2050	**-0.40**	-0.35	-0.37	-0.07	-0.17	-0.38	-0.22	-0.22	0.10	-0.10	-0.05	-0.26	**-0.44**	**0.45**	0.31	0.29

II. R&D Policy Scenarios

N. Kouvaritakis and V. Panos (PROMETHEUS) ICCS-NTUA
P. Criqui and S. Mima (POLES) LEPII-EPE
H. Turton (ERIS) IIASA
L. Barreto and S. Kypreos (GMM) PSI
M. Blesl, U. Fahl and U. Kumar Rout (TIMES) IER

1. Introduction

One of the most fundamental issues addressed within the SAPIENTIA project has been the importance of R&D (and in particular public R&D) in influencing the energy system towards sustainability. To explore this issue, three scenarios of future R&D support have been developed: a "High R&D Scenario", implying the doubling of total energy-related R&D (Government and Private for the whole world) on the technologies covered within SAPIENTIA over the period 2006-2025, an "R&D Doubling" (or optimistic) Scenario implying a doubling of total R&D (GERD and BERD for the whole world) over the period 2006-2010 and a "Zero GERD" (or pessimistic) scenario, implying the elimination of Government energy-related R&D (GERD) worldwide from the whole Outlook (to 2050).

The two scenarios have been constructed to represent changes in R&D of a similar magnitude. The structure of government and total energy related R&D budget has to some extent influenced the outcome of these two scenarios. The public R&D budget outlook is dominated by conventional and advanced nuclear power research, which amounts to slightly above half the total Government R&D funding. Renewable energy technologies attract 15% of the budget, almost half of which is directed to Photovoltaics. Clean coal technologies obtain over 7 percent, whereas Fuel Cells and non-conventional vehicles attract around 4 percent each. On the other hand, the Private R&D allocation is dominated by conventional vehicle technologies, which absorb over one third of the budget. Renewables account for over 15 percent, while Fuel Cells figure with a larger share relative to public R&D allocation (6%). Nuclear power is restricted to low shares in private research funding (4%), whereas non-conventional vehicles and clean coal technologies attract limited shares (1.8 and 1 percent respectively).

2. ERIS Results

The baseline scenario described in the previous section illustrates just one possible configuration of future technological and energy system development. Of particular interest here is the future uncertainty associated with technology policies, and the implications this has for the future uptake of new technologies, transformation of the energy system, and the impact on sustainability. To explore this aspect of uncertainty, this section examines sustainable development under two alternative scenarios of future public R&D support – one scenario where public energy R&D is double the level described in Section D 1.3 and one where it is zero. Hereafter we refer to these as the «R&D Doubling» and "Zero R&D" scenarios, respectively.

Apart from alternative R&D investment, all other factors affecting the development of the energy system under these scenarios are identical to the baseline. Accordingly, this exercise helps to illustrate the specific impact of enhanced or diminished energy R&D support. This section presents the impact of these alternative scenarios on technology choice in key energy sectors and on each of the sustainability indicators of interest, relative to the baseline.

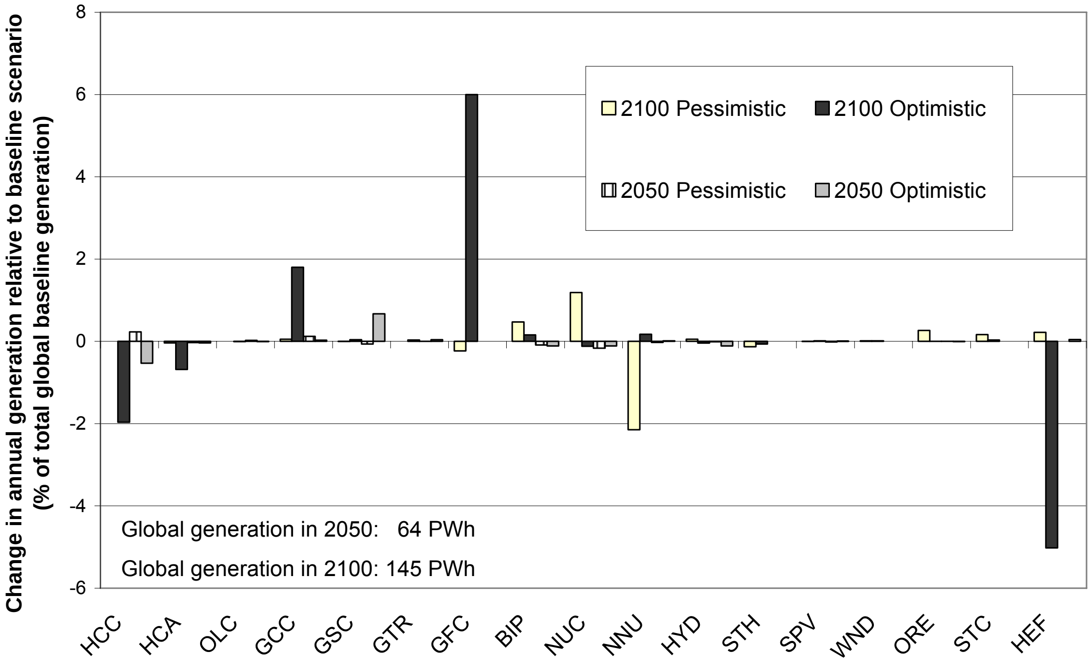
2.1. Technology deployment

Looking first at the effect of the «R&D Doubling» and «Zero GERD» future energy R&D investment on the development of the electricity sector, Figure 2-1: presents generation technology choice relative to the baseline scenario. Figure 2-1: shows the change in generation from each technology resulting from the alternative R&D scenarios as a percentage of total generation in 2050 and 2100. Even though the impacts are presented as a percentage, the inertia in the energy system means that the greatest effects are not observed until later in the century.

Electricity generation under the «Zero GERD» scenario is almost identical to the baseline scenario up until 2050, and even by 2100 the divergence is small. This implies that other factors, such as the climate policy and resource constraints, have a greater influence on technology choice than government energy R&D, if we assume the levels under the baseline scenario. The most significant effect of the lower energy R&D investment in this «Zero GERD» scenario is to delay the development of 4th generation nuclear reactors. As a consequence, one of the few ways that the energy system can meet rising demand while responding to the climate policy assumed to apply in this scenario is to rely more heavily on 3rd generation nuclear reactors, with some additional generation from coal, biomass and some other renewables.

The «R&D Doubling» scenario results in a more significant, although still small transformation of the global electricity sector by 2100 by promoting gas fuel cell and combined cycle generation almost entirely at the expense of hydrogen fuel cell and coal-based generation. However, the gas and hydrogen fuel cell technologies are very similar, and affected by R&D investment in much the same way so this result cannot be attributed to any purely technological edge of gas fuel cells in electricity generation, and instead must be related to other factors, including cost and availability of gas and hydrogen. Similarly, the shift away from coal-fired generation can be attributed partly to the impact of the climate change mitigation policy, but it remains unclear how the higher levels of R&D investment are able to increase the contribution of gas-based electricity generation, remembering that in the baseline scenario gas became increasingly scarce towards the end of the century. To answer this question we clearly need to explore the development of other energy sectors, which we briefly discuss below.

Figure 2-1: Change in global generation under alternative R&D scenarios, relative to baseline (2050, 2100)



Note: Technology abbreviations are as follows: HCC: conventional coal, HCA: advanced coal (IGCC), OLC: oil conventional, GCC: gas combined-cycle, GSC: gas steam cycle, GTR: gas turbine, GFC: gas fuel cell, BIP: biomass gasification, NUC: nuclear conventional, NNU: new nuclear, HYD: hydro, STH: solar thermal, STC: solar thermal cogeneration, SPV: solar photovoltaics, WND: wind turbine, ORE: other renewables, HEF: hydrogen fuel cell.

One potentially important sector is transportation, where a number of new technologies, including new powertrains (such as fuel cells and hybrids) and new energy systems (such as advanced batteries, reformers and hydrogen storage) compete. However, as shown in Figure 2-2, a reduction in government energy R&D has little impact on the future choice of transportation technologies under the assumptions used here. The necessity to shift away from, or use more efficiently oil and gas resources is a more pressing concern than avoiding technologies that are slightly more expensive because of lower R&D support – in other words, it is still attractive to deploy technologies such as hybrid vehicles under this «Zero GERD» scenario, even though lower R&D investment means they are less mature.

These same factors affect technology choice under the "R&D Doubling" investment scenario, but the additional R&D instead accelerates technology development. The impact is shown in Figure 2-3 where by expanding the suite of competitive vehicle technologies the «R&D Doubling» scenario radically transforms the development of this sector. Figure 2-3 shows a rapid transition from the conventional gasoline ICE through alcohol ICEs and gas hybrids to hydrogen fuel cell vehicles.

Clearly, the additional R&D investment creates a more effective and competitive way of meeting climate change mitigation goals and reducing reliance on fossil fuels. This occurs almost entirely because of the impact of the additional R&D on fuel cell competitiveness (see Appendix, Tables A1 and A2). This in turn facilitates an earlier penetration of this technology into both stationary and mobile markets, which in turn leads to additional learning-by-doing and further improvements in competitiveness.

Figure 2-2: Global technology and fuel choice for passenger car travel, «Zero GERD» R&D scenario (with GHG abatement policy)

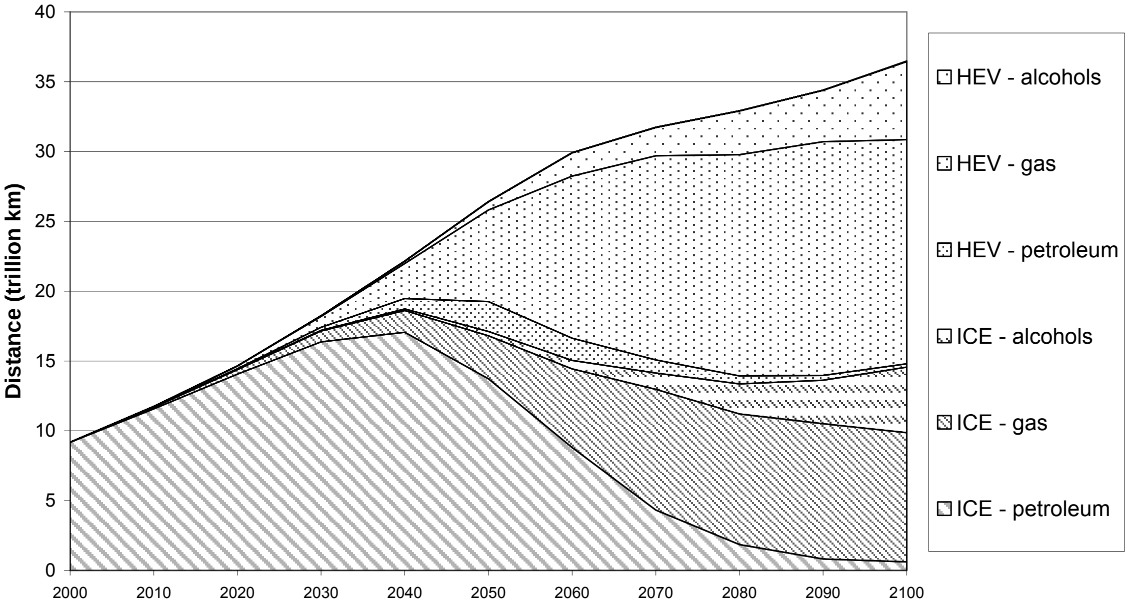
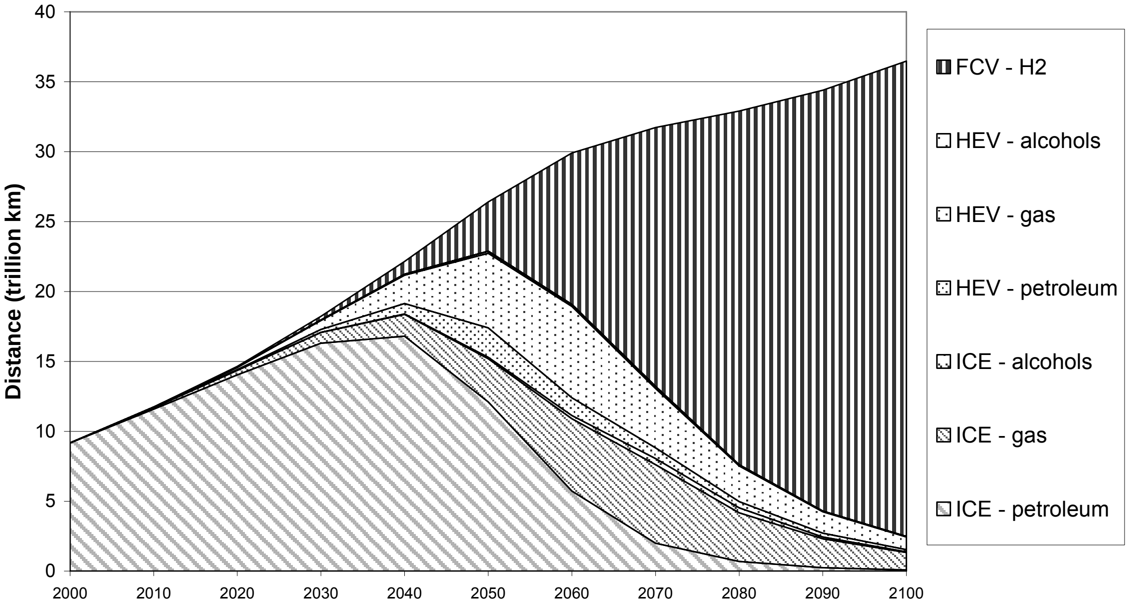


Figure 2-3 Global technology and fuel choice for passenger car travel, «R&D Doubling» scenario (with GHG abatement policy)



This overall transformation of the passenger transport sector under this «R&D Doubling» scenario provides one explanation for the results observed in Figure 2-1: for the electricity sector. Specifically, the lower reliance on natural gas in the transport sector allows greater use of gas in electricity generation. As we saw in Table 2-2 even under the baseline scenario gas-fired electricity generation technologies were among the most competitive, so it is not surprising that under this «R&D Doubling» scenario there is more generation from natural gas. Moreover, the quantity of hydrogen demanded by the transport sector reduces availability in other sectors, which partly explains the preference for gas over hydrogen fuel cells in electricity generation under the «R&D Doubling» scenario (see Figure 2-1:).

One would assume that such a marked shift to an alternative development path may have implications for sustainable development, particularly since there appears to be greater reliance on low- and zero-emissions fuels under the «R&D Doubling» scenario. The following section examines the impact of this alternative development path on indicators of sustainable development.

2.2. Sustainability indicators

The impact on greenhouse gas emissions of the two alternative government energy R&D scenarios relative to the baseline scenario is presented in Figure 2-4. Not surprisingly, the impact under the «Zero GERD» scenario is very small, which is consistent with the relatively unchanged development path of the energy system under this scenario. The «R&D Doubling» scenario also has relatively little impact on emissions until late in the century, where it contributes to a substantial decline (2 Gt C-e pa) in total annual emissions. However, as shown in

Figure 2-5, this results in only a relatively small decline in atmospheric CO_2 concentrations relative to the baseline scenario, because emissions for most of the century are only slightly below the baseline trajectory. The «Zero GERD» scenario leads to an atmospheric CO_2 concentration almost identical to that under the baseline scenario.

Moving along the causal chain from emissions through to climate impacts, Figure 2-6 presents the change in average global temperature compared to the baseline scenario. These impacts on temperature are small, and somewhat counter-intuitive – for example, the lower emissions and CO_2 concentrations under the «R&D Doubling» scenario result in a higher temperature because emissions of sulfur oxides (SO_x) (from coal combustion and a precursor of sulfate aerosols with negative forcing) are also reduced under this scenario. Accordingly, in Figure 2-6 we also show the impact on temperature assuming constant levels of atmospheric sulphate, which exhibits a path that is more consistent with emissions and concentrations. However, this is an artificial construction since SO_x emissions are declining in all scenarios and this is merely accelerated under the «R&D Doubling» scenario because of a faster phase-out of coal.

Importantly, however, for essentially all of the climate change indicators the most significant change occurs at the end of the century. Accordingly, for the remainder of this analysis of climate change indicators and impacts in this report we focus on the year 2100.

<u>Figure 2-4 Change in global GHG emissions under alternative R&D policy scenarios, relative to baseline</u>

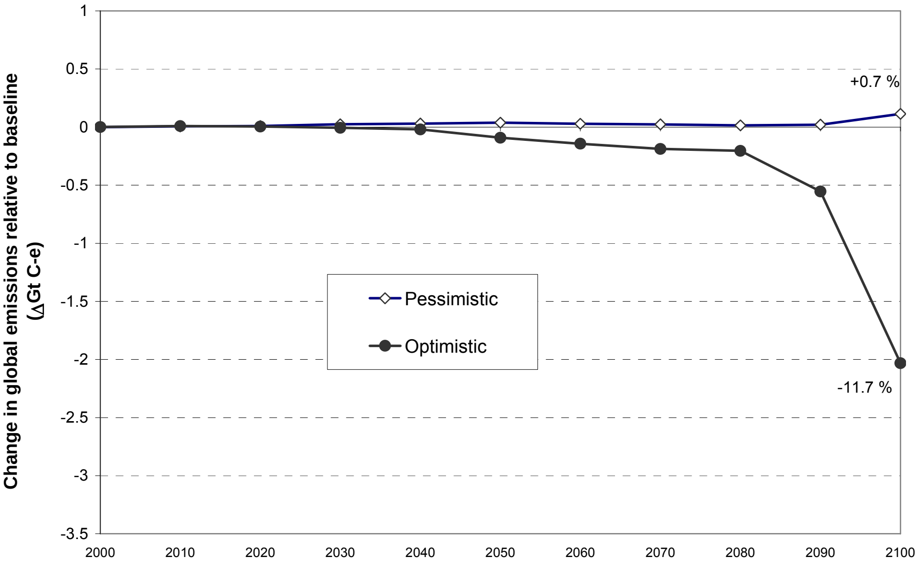


Figure 2-5 Change in atmospheric CO_2 concentrations under alternative R&D scenarios, relative to baseline

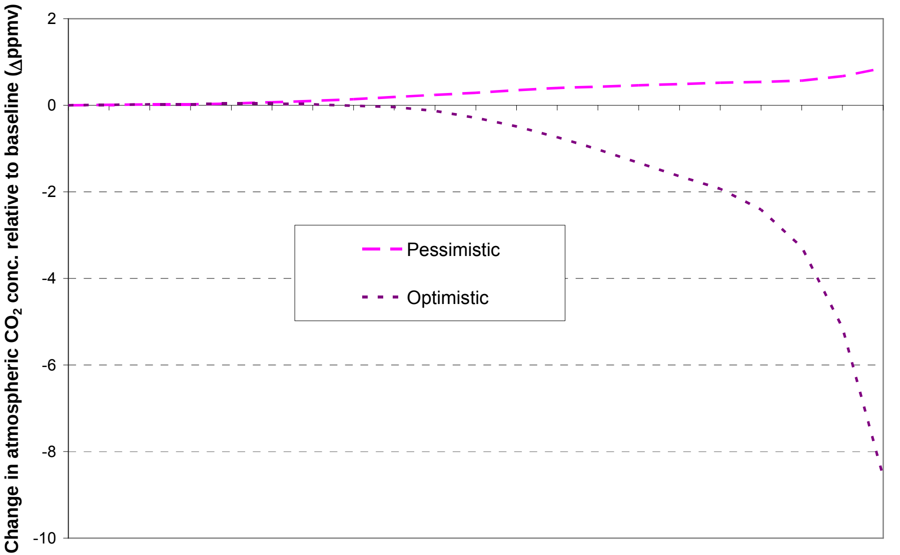
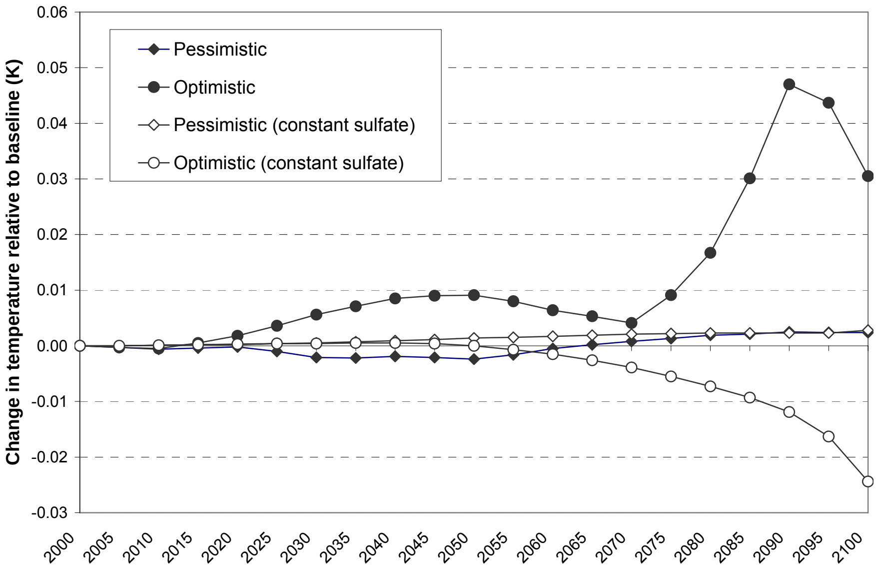


Figure 2-6 Change in global temperature and sea level under alternative R&D scenarios, relative to baseline



Turning now to the other set of indicators of sustainability, the effect on security of oil supply of the «R&D Doubling» and elimination of government energy R&D scenarios is presented in Figure 2-7. This figure shows the change in the global resources-to-production ratio (R:P), and the change in the resources-to-consumption ratio (R:C) in Europe (comprising Europe up to the borders of the Former Soviet Union). It should be remembered that this *resources*-to-production ratio differs from the commonly reported *reserves*-to-production ratio (for example, BP 2004), in that it is based on total recoverable resources, rather than current levels of identified reserves. Looking at the results for R:P and R:C, for most of the first half of the 21st century neither policy has a significant impact on the energy security ratios, but this changes by 2040-2050. Between

2050 and 2070, under the «R&D Doubling» scenario the resources-to-production ratio for oil is extended by 1.1-1.9 years, equivalent to up to a 6 percent increase in the ratio, which may be sufficient to reduce vulnerability to supply disruptions. At the same time, the resource-to-consumption ratio for oil in Europe is increased by a similar relative amount. However, this coincides with a larger (although transient) reduction in the R:C ratio for gas in Europe (see Figure 2-8).

This improvement in oil supply security under the «R&D Doubling» scenario is most likely indirectly attributable to the rapid shift to fuel cell vehicles. As discussed this alternative development path for the transportation sector alleviates some pressure from this sector on natural gas resources compared to the baseline scenario. Gas is a relatively low-emissions, clean and convenient fuel and the supplies freed up by a shift to hydrogen fuel cell vehicles can be used in other sectors, including in electricity generation, direct combustion and other forms of transport, where the greenhouse policy favours gas over oil. As a consequence, oil demand is reduced and the lifespan of resources is extended. However, this change does not persist, and increasing natural gas scarcity means that these expanded oil resources are eventually exploited (as seen in Figure 2-7).

This preference for natural gas means that under the «R&D Doubling» scenario the global resources-to-production ratio for this fuel is reduced early in the century (troughing in 2030), as seen in Figure 2-8, but the shift back to oil towards the end of the century eventually improves gas security of supply compared to the baseline. The «Zero GERD» scenario, however, has a much smaller impact. Critically for long-term security of supply, the largest reduction in the global R:P ratio occurs at a time when global gas resources are still relatively abundant (2030, see Figure 2-7). This means this decline is less likely to have a significant impact on the likelihood or severity of supply disruptions. However, in Europe the largest decrease in the R:C ratio occurs in 2060, at a time when cheap gas resources have been largely exhausted, posing a potentially larger threat. Accordingly, for both oil and gas we focus on this period in subsequent analysis throughout this report.

Figure 2-7 Change in global and European oil resource-to-production and -consumption ratios under alternative R&D scenarios, relative to baseline

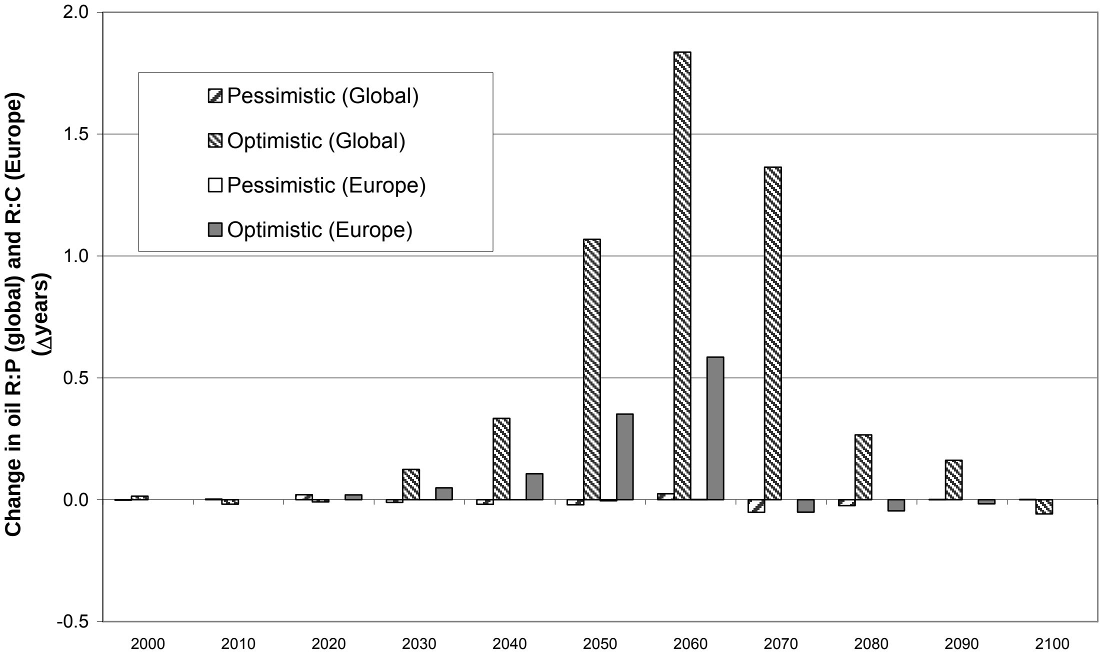
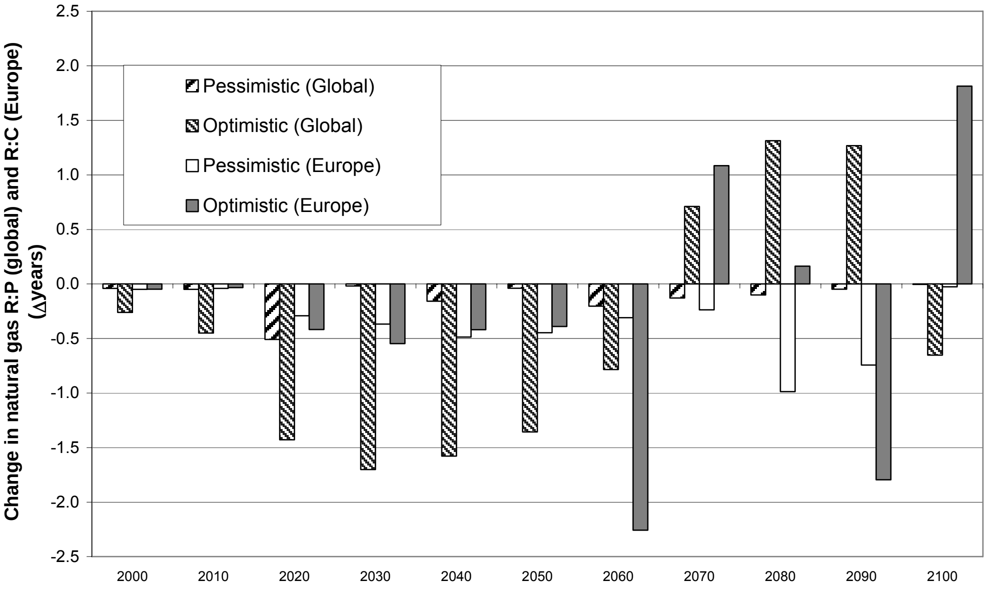


Figure 2-8 Change in global and European gas resource-to-production and -consumption ratios under alternative R&D scenarios, relative to baseline



2.3. Impacts

As already discussed, we are also interested in measuring the impact of a change in R&D investment on the indicators of sustainability described above. This impact is defined as the change in the indicator, divided by the change in expenditure. Although this formulation is defined specifically for the standardised R&D shock exercise in the following section, it is possible to apply it to these «R&D Doubling» and «Zero GERD» scenarios.

We have already seen the change in the various indicators which represent the sustainable-development objectives of interest, so it is a relatively simple matter to divide these changes by the change in global government R&D expenditure relative to the baseline scenario. In the baseline scenario, government energy R&D investment on the technologies included in this modelling framework amounted to approximately €400 billion (undiscounted) between 2000 and 2050. Accordingly, the «R&D Doubling» scenario is based on expenditure of around double this amount, while government energy R&D expenditure is eliminated in the «Zero GERD» scenario.

The impacts per billion euros of R&D expenditure under these scenarios are presented in Table 2-1: . The units for the impact on each indicator are also indicated. So, for example, additional expenditure per year of $100 billion over the next 50 years reduces atmospheric CO_2 concentrations by approximately 2 ppm. On the other hand, reducing R&D expenditure by the same amount would increase concentrations by only 0.2 ppm. Similar differences in the impact magnitude between increases and decreases are observed for all indicators in Table 2-1: . This is consistent with the results for the «Zero GERD» scenario, which do not diverge substantially from the baseline scenario results.

Table 2-1: Impacts on sustainability indicators of alternative R&D scenarios

Indicator	Impact Reduced investment (Zero GERD)	Additional investment (R&D Doubling)	Units
CO_2 conc. (2100)	-2.0E-03	-2.0E-02	ppm/€bn
CH_4 conc. (2100)	1.6E-03	-1.7E-02	ppb/€bn
Temperature (2100)	-5.6E-06	7.2E-05	K/€bn
Temperature (2100) (constant sulfate)	-6.6E-06	-5.7E-05	K/€bn
Sea-level (2100)	-4.7E-05	4.5E-04	cm/€bn
Security of oil supply (2060)	-5.7E-05	4.3E-03	years/€bn
Security of gas supply (2060)	4.8E-04	-1.8E-03	years/€bn

The fact that the «Zero GERD» scenario does not diverge from the status quo implies that the level of government energy R&D investment assumed in the baseline scenario has a relatively insignificant impact on energy system development compared to that of other factors, such as the climate policy and resource constraints. This is not to say there is no place for government R&D in promoting new energy technologies, and the potential for such investment to transform the energy system is demonstrated by the impact of the «R&D Doubling» scenario. Clearly, the relationship between total R&D expenditure and the impact on indicators of sustainable development is non-linear. However, this analysis also shows that simply doubling energy R&D with little forethought in terms of overall strategy, targeting and consistency with other goals, is a very expensive way to achieve policy objectives. The next section (D 3) attempts to go some way towards identifying the specific technologies that represent key targets for policy support and future R&D investment, with the aim of developing more cost-effective strategies for achieving desired sustainability outcomes.

3. GMM Results

In this section, the impact of changes in the energy-related R&D expenditures on sustainability indicators using the GMM model is examined. Several scenarios of R&D spending have been constructed. The first optimistic scenario, labeled “R&D doubling” portrays the effects of a doubling of the energy-related R&D funding for the period 2005-2010, as specified within SAPIENTIA. An alternative optimistic scenario, labeled “High R&D” presents a more extreme situation with a much higher increase in energy-related R&D expenditures. The third scenario, labeled “zero GERD”, illustrates the consequences of an absence of energy-related government R&D expenditures, as specified in SAPIENTIA. These scenarios represent extreme situations that may not come to occur in reality. They are used here to ensure that measurable impacts on the sustainability indicators can be measured. Where appropriate, the results of these scenarios are compared to those of the baseline scenario, which follows the R&D spending specified in the SAPIENTIA R&D outlook (Kouvaritakis, 2005b).

In conducting this exercise, the two-factor learning curve (2FLC) specifications estimated by Kouvaritakis and Panos (2005a) for the technologies under examination within SAPIENTIA were used to the extent possible and within the limitations of the perfect-foresight modeling approach used in this study and described above. Specifically, it should be noticed that the GMM model only includes learning curves for investment costs of technologies. The effects of technological learning on fixed and variable operation and maintenance (O&M) costs and on efficiency are not included. This may lead to an underestimation of the impacts of an increase on R&D expenditures on technological progress and technology diffusion. In addition, the learning-by-doing and learning-by-searching elasticities used here are time independent and are not assumed to decrease and/or saturate over time.

3.1. “R&D Doubling” Scenario

This SAPIENTIA scenario, labeled “R&D doubling”, portrays the effects of a doubling of total energy-related R&D expenditures (i.e. government and business-related for the whole world) specified in the SAPIENTIA R&D outlook between the years 2005 and 2010 on all technologies under examination here (see Table 3-1 below). That is, it constitutes a moderately optimistic scenario. The time evolution of the sustainability indicators in the R&D doubling scenario is compared to the trajectories of the same indicators in the baseline scenario in Figure 3-1 and Figure 3-2.

Figure 3-1: Comparison of climate-change sustainability indicators in the baseline and R&D doubling SAPIENTIA scenarios.

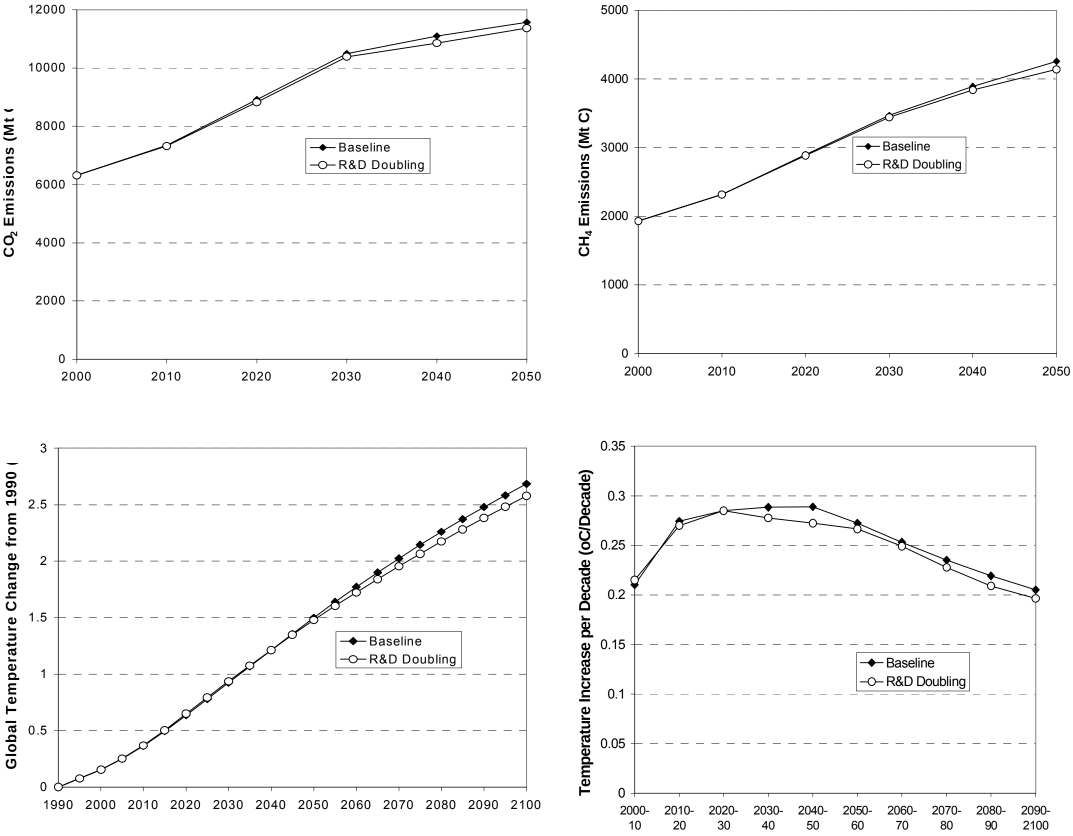


Figure 3-2: Comparison of sustainability indicators in the areas of security of energy supply and transport in the baseline and R&D doubling scenarios.

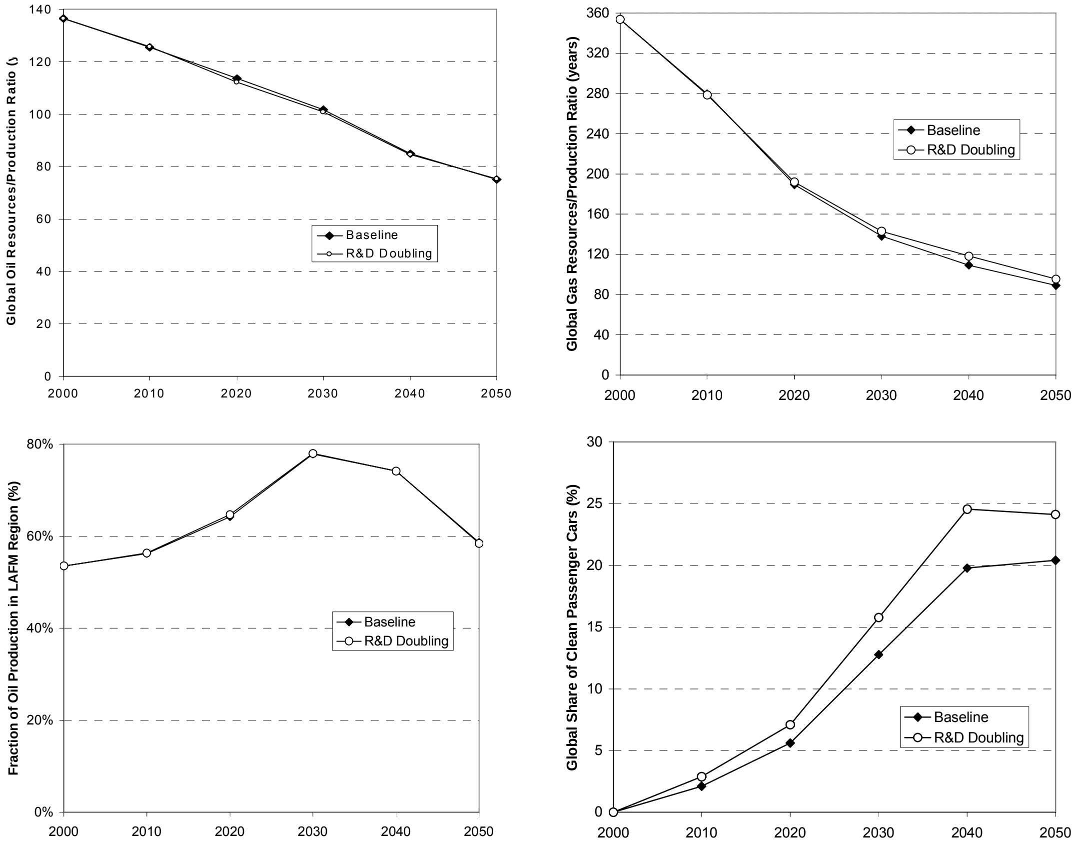


Table 3-1 presents a summary of the sustainability indicators under examination here for the R&D doubling and the baseline scenario. As stated above, very small improvements can be observed.

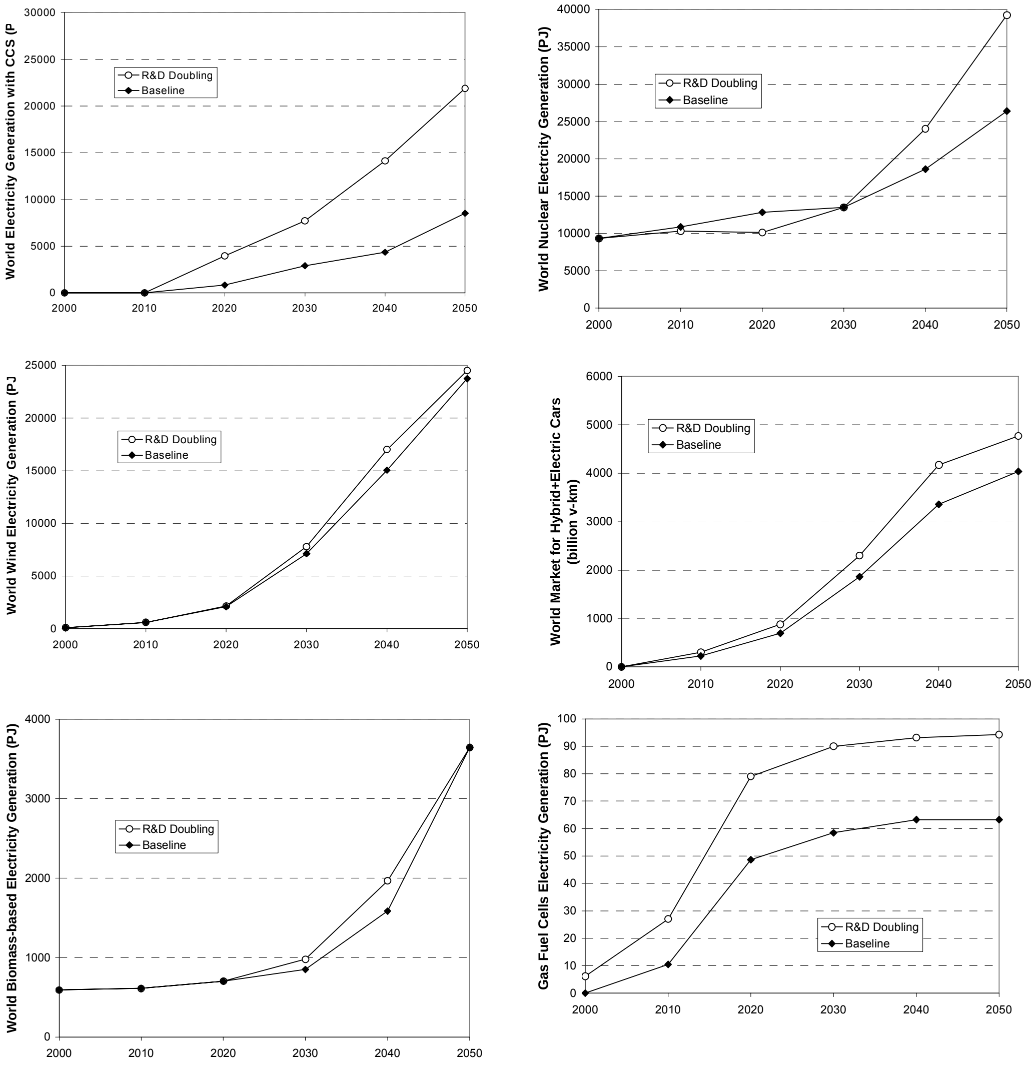
Table 3-1 Summary of changes in sustainability indicators in the R&D doubling scenario compared to the baseline scenario.

Sustainability Indicator	Unit	Baseline	R&D Doubling	Change (%)
Cumulative CO_2 emissions 2000-2050	Gt C	557.3	550.7	-1.2
Cumulative CH_4 emissions 2000-2050	Gt C-eq	187.7	185.5	-1.2
Global temperature change commitment in 2065 (from 1990)	°C	1.90	1.85	-2.6
Highest temperature increase per decade 2000-2050	°C/decade	0.289	0.285	-1.3
Global Oil Ru/P ratio in 2050	Years	75.11	75.3	0.3
Global Gas Ru/P ratio in 2050	Years	89	95.2	7.0
Fraction of oil production from the LAFM region in 2050	%	0.59	0.59	0.0
Market share of clean passenger cars in 2050	%	20.4	24.0	17.6

As can be seen, the doubling of R&D expenditures leads to very modest improvements in the climate-change indicators. As for the indicators of security of energy supply related to oil production, the impact is also very modest. In contrast, there is an improvement in the world share of clean passenger cars in the year 2050. The impacts of the R&D doubling scenario are limited by the fact that a considerable increase of R&D expenditures already takes place in the baseline scenario (Kouvaritakis, 2005b).

Figure 3-3 presents a summary of deployment of selected technologies in the R&D doubling scenario, namely power plants with CO_2 capture and storage (mainly coal and biomass-based IGCC power plants and natural gas combined-cycle turbines), nuclear power generation, wind turbines, biomass-based electricity generation, stationary gas fuel cells for electricity generation and hybrid and electric passenger cars. For comparison, the deployment of these technologies in the baseline scenario is reported as well.

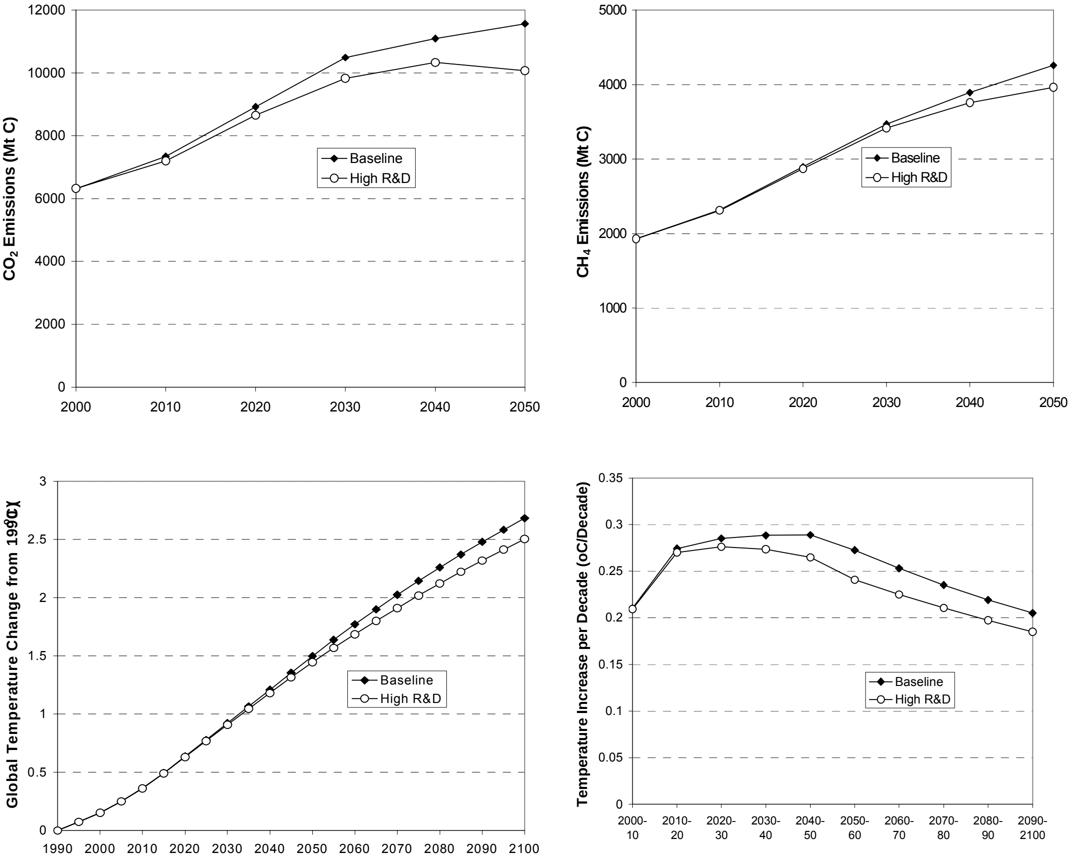
Figure 3-3: Global deployment of selected technologies in the R&D doubling scenario and comparison with uptake in the baseline scenario. The abbreviation CCS stands for CO_2 capture and storage.



3.2. “High R&D” scenario

We have developed an alternative, high R&D-spending, scenario. This scenario labelled “High R&D” has been constructed assuming a doubling of the R&D expenditures specified in the SAPIENTIA R&D outlook between the years 2000 and 2025. Thus, it represents a much higher R&D spending than the standard SAPIENTIA “R&D doubling” scenario examined above. The time evolution of the sustainability indicators in the “high R&D” scenario is compared to the trajectories of the same indicators in the baseline scenario in Figure 3-1 and Figure 3-2.

Figure 3-4: Comparison of climate-change sustainability indicators in the baseline and high R&D scenarios.



<u>Figure 3-5: Comparison of sustainability indicators in the areas of security of energy supply and transport in the baseline and high R&D scenarios.</u>

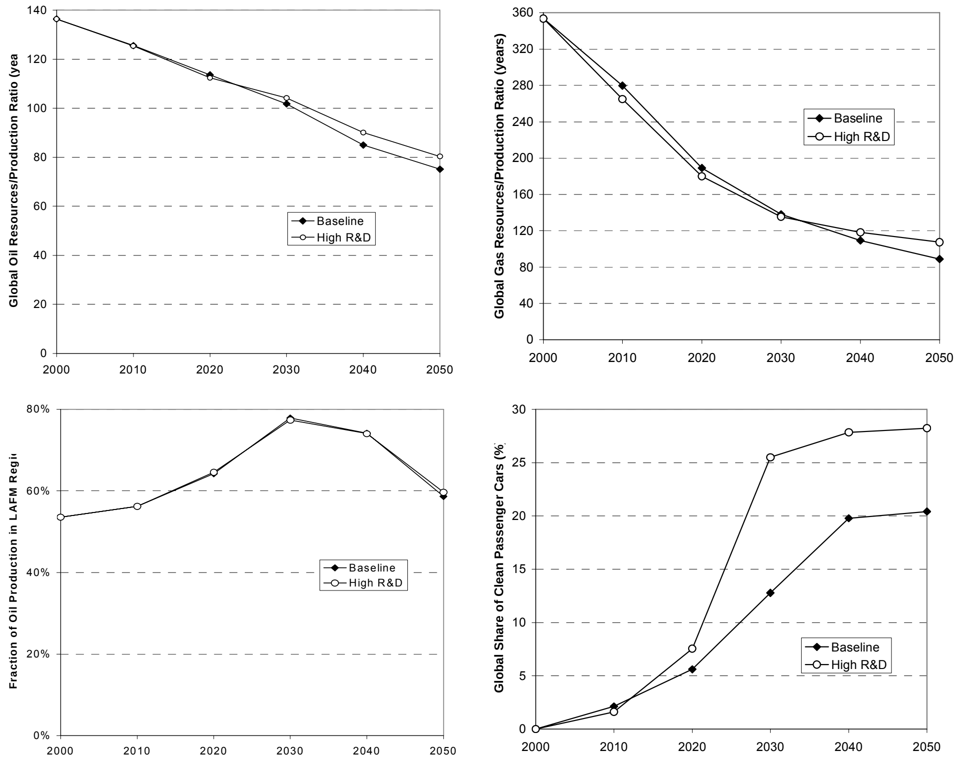


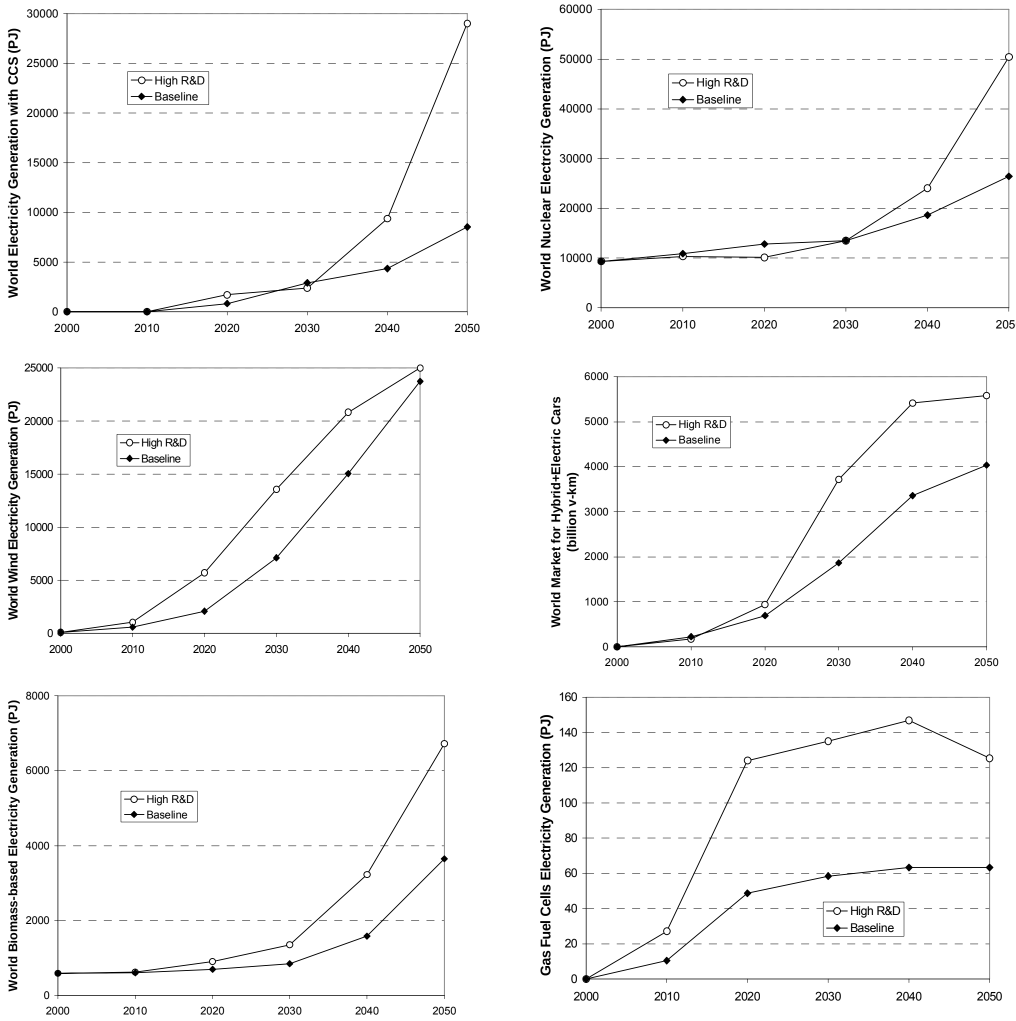
Table 3-1 presents a summary of the sustainability indicators under examination here for the R&D doubling and the baseline scenario. As stated above, significant improvements can be observed.

<u>Table 3-2: Summary of changes in sustainability indicators in the high R&D scenario compared to the baseline scenario.</u>

Sustainability Indicator	Unit	Baseline	High R&D	Change (%)
Cumulative CO_2 emissions 2000-2050	Gt C	557.3	524.1	-6.0
Cumulative CH_4 emissions 2000-2050	Gt C-eq	187.7	182.6	-2.7
Global temperature change commitment in 2065 (from 1990)	^{o}C	1.90	1.80	-5.3
Highest temperature increase per decade 2000-2050	^{o}C/decade	0.29	0.27	-6.9
Global Oil Ru/P ratio in 2050	years	75.11	80.31	7.0
Global Gas Ru/P ratio in 2050	years	89	107	20.2
Fraction of oil production from the LAFM region in 2050	%	0.59	0.60	1.7
Market share of clean passenger cars in 2050	%	20.4	28.2	38.2

Figure 3-3 presents a summary of deployment of several technologies for which high R&D expenditures result in a substantially increased uptake, namely power plants with CO_2 capture and storage (mainly coal and biomass-based IGCC power plants and natural gas combined-cycle turbines), nuclear power generation, wind turbines, biomass-based electricity generation, stationary gas fuel cells for electricity generation and hybrid and electric passenger cars. For comparison, the deployment of these technologies in the baseline scenario is reported as well.

Figure 3-6: Global deployment of selected technologies with increased uptake in the high R&D scenario and comparison with uptake in the baseline scenario. The abbreviation CCS stands for CO_2 capture and storage.

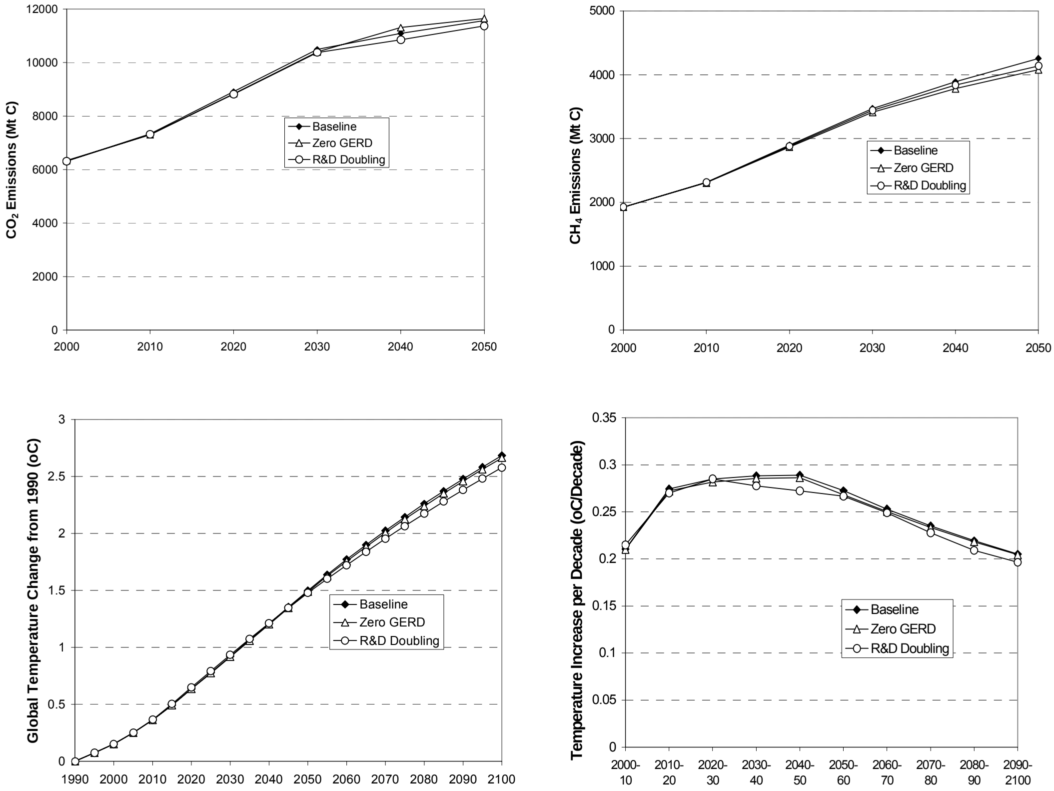


As can be seen, high R&D expenditures lead to improvements in the climate-change indicators. As for the indicators of security of energy supply related to oil production, the impact is modest. In contrast, there is a considerable improvement in the gas Ru/P ratio for the year 2050, mainly due to the displacement of gas combined-cycle electricity generation by nuclear power. In addition, there is a substantial improvement in the world share of clean passenger cars in the year 2050. This scenario illustrates the fact that if significant impacts on these sustainability indicators were to be achieved through R&D alone, a substantial increase in R&D expenditures would be necessary. This provides a rationale for a meaningful combination of R&D with other policy instruments (e.g. demonstration and deployment programs).

3.3. “Zero GERD” Scenario

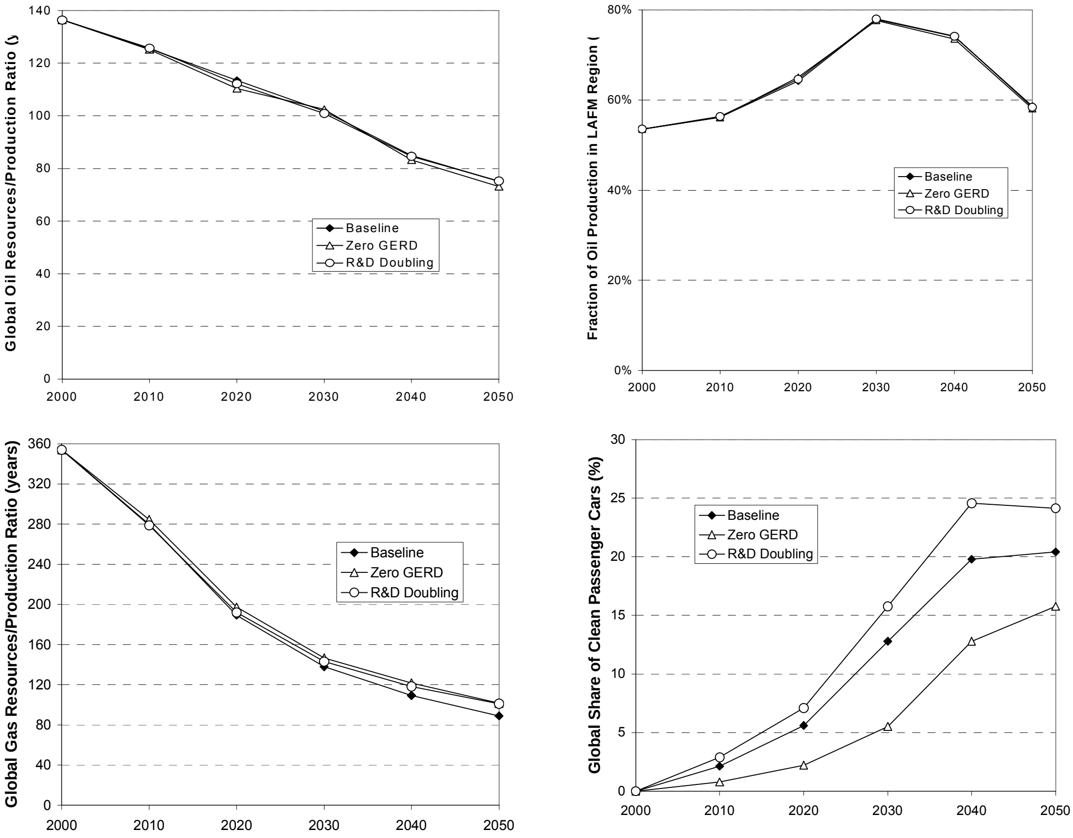
This scenario portrays the effects of an elimination of government energy-related R&D (GERD) for the whole world on the technologies under consideration in this analysis for the period 2000-2025. The time evolution of the sustainability indicators in the “zero GERD” scenario is compared to the trajectories of the same indicators in the baseline and “R&D doubling” scenario in Figure 3-7 and Figure 3-8.

Figure 3-7: Comparison of climate-change sustainability indicators in the baseline, “zero GERD” and “R&D doubling” scenarios.



It should be noticed that the baseline scenario already includes a climate policy, represented by differentiated CO_2 taxes imposed on the different regions. The effect of removing government-sponsored R&D is a change in the relative ranking of technologies and, therefore, in the way this CO_2 policy target is fulfilled. That is, with the reduction of R&D funding, changes in the cost profiles of the technologies occur. Specifically, the options that are not competitive today are negatively affected. Consequently, the composition of the mitigation strategy changes in favor of technologies that are already competitive today. Specifically, the role of nuclear power plants (generation III, III+) increases significantly with respect to the baseline, mainly displacing electricity generation from natural gas combined-cycle turbines. Under these circumstances, climate-change indicators remain at similar levels than in the baseline scenario. However, CH_4 emissions are somewhat reduced, mainly due to the fact that a reduction in the consumption of natural gas takes place in the electricity sector. As a result, the global temperature change and highest rate of temperature change per decade are slightly lower in the “zero GERD” scenario than in the baseline scenario. It should, however, under no means be understood that eliminating GERD is a way of improving of climate-change indicators.

Figure 3-8: Comparison of sustainability indicators in the areas of security of energy supply and transport in the baseline and the "zero GERD" and "R&D doubling" scenarios.



As for the indicators of security of energy supply, in the zero GERD scenario there are no noticeable changes in the oil Ru/P ratio for the year 2050 and the fraction of oil produced in the LAFM region. In contrast, there is an improvement in the gas Ru/P ratio due to the reduced natural gas consumption as explained above. As for the transportation sector, a substantial reduction of the market share of clean cars takes place.

Table 3-3 presents a summary of the changes in the sustainability indicators under examination here in the "zero GERD" scenario compared to the baseline scenario. As mentioned before, climate-change indicators remain at similar levels to those of the baseline scenario. There is an improvement in the global gas Ru/P ratio while deterioration can be noticed in the fraction of clean vehicles and the global oil Ru/P ratio for the year 2050.

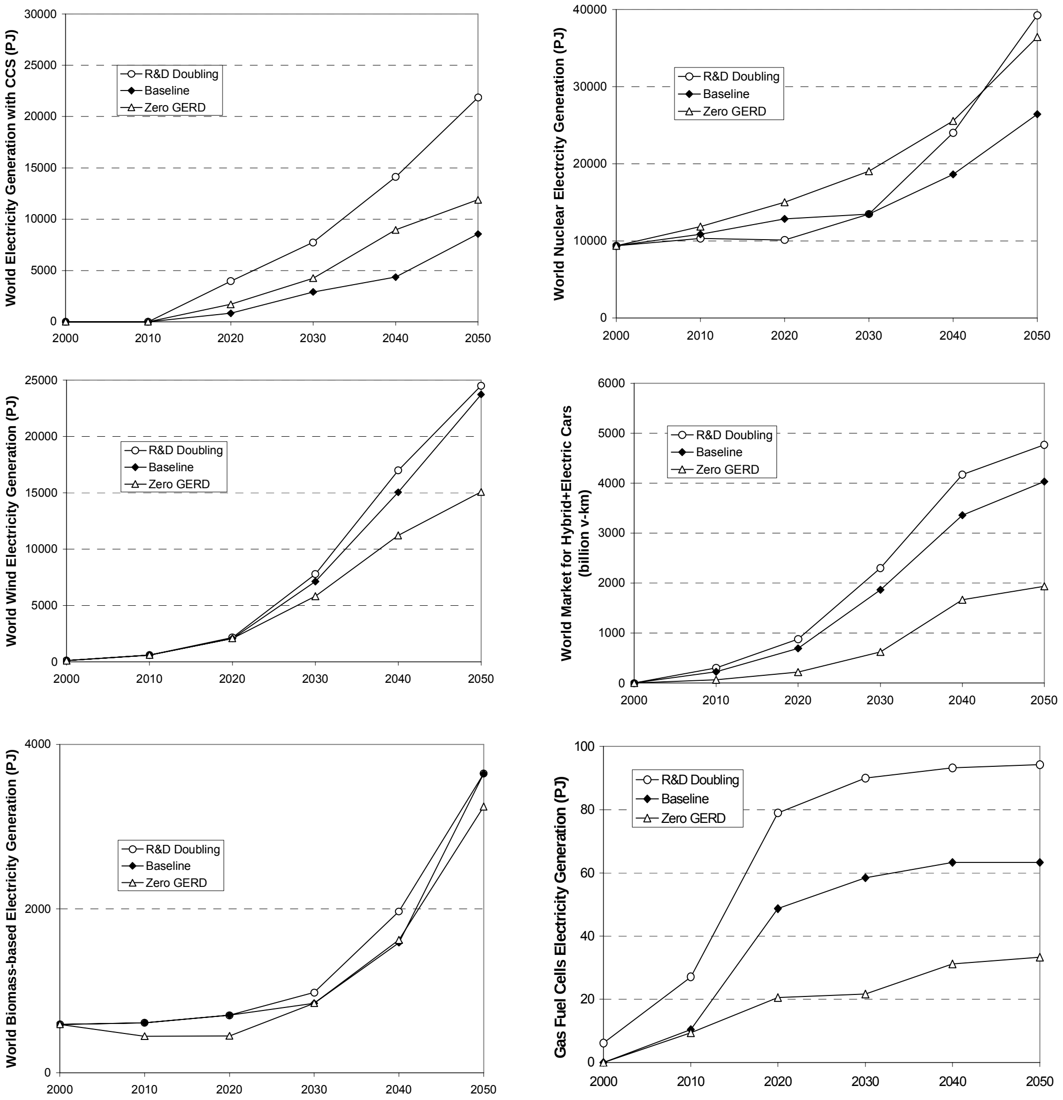
Table 3-3: Summary of changes in sustainability indicators in the "zero GERD" scenario compared to the baseline scenario

Sustainability Indicator	Unit	Baseline	Zero GERD	Change relative to Baseline (%)
Cumulative CO_2 emissions 2000-2050	Gt C	557.3	558.4	+0.2
Cumulative CH_4 emissions 2000-2050	Gt C-eq	187.7	183.9	-2.0
Global temperature change commitment in 2065 (from 1990)	^oC	1.90	1.88	-0.9
Highest temperature increase per decade 2000-2050	^oC/decade	0.29	0.286	-1.3
Global Oil Ru/P ratio in 2050	years	75.1	73.2	-2.5
Global Gas Ru/P ratio in 2050	years	89	101.7	14.2
Fraction of oil production from the LAFM region in 2050	%	0.59	0.58	-1.6
Market share of clean passenger cars in 2050	%	20.4	15.77	-22.7

Figure 3-9 presents a summary of deployment over time for the same technologies discussed in section 3.1 above, namely power plants with CO_2 capture and storage (mainly coal and biomass-based IGCC power plants and natural gas combined-cycle turbines), conventional nuclear power generation, wind turbines, biomass-based electricity generation, stationary gas fuel cells for electricity generation and hybrid and electric passenger cars. For comparison, the deployment of these technologies in the baseline and R&D doubling scenarios is reported as well.

As can be seen in Figure 3-9, there is an increase in electricity generation from conventional nuclear power plants (generation III, III+) and fossil power plants with CO_2 capture and storage (mainly coal and biomass-based IGCC power plants and natural gas combined-cycle turbines) in the zero GERD scenario as compared to the baseline scenario. In the case of nuclear power plants, output levels are higher in the "zero GERD" scenario than in the "R&D doubling" scenario, with the exception of the final period of the time horizon (the year 2050). In contrast, the electricity production from biomass-based power plants remains at similar levels to those of the baseline scenario. The market fraction of hybrid and electric cars and the output of gas-powered fuel cells and wind turbines are substantially reduced in the "zero GERD" scenario.

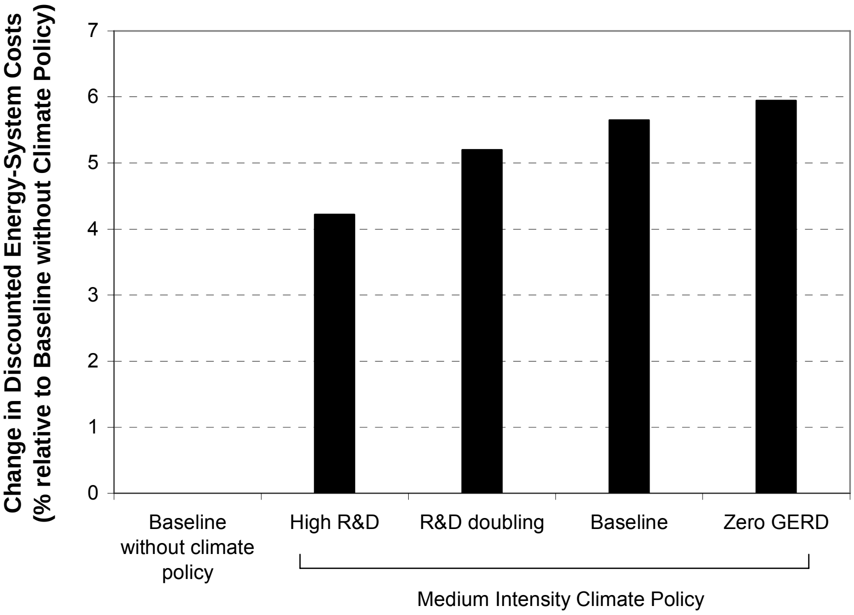
Figure 3-9: Global deployment of selected technologies in the "zero GERD" scenario and comparison with uptake in the baseline and "R&D doubling" scenarios. The abbreviation CCS stands for CO_2 capture and storage.



In order to illustrate the impact of R&D in the costs of the energy system, we now compare the difference in total discounted energy-system costs between the different R&D spending scenarios examined in this study. The perfect-foresight GMM model minimizes total discounted energy-system costs over the whole time horizon. These costs refer to the summation of all investment, operation and maintenance and fuel costs of the global energy system for the whole time horizon of the model analysis (2000-2050) discounted to the starting year (2000). The discount rate used for these calculations is 5%. The "zero GERD" scenario results in an increase of 0.3%, or 307 billion Euro of the year 2000 relative to the baseline scenario. The reduction in the "R&D doubling" scenario is very modest, amounting to 0.4% or 469 billion Euro. The "High R&D" scenario results in a substantial decrease of 1.3%, or 1500 billion Euro of the year 2000 relative to the baseline scenario. These costs do not include discounted R&D expenditures.

Using these figures for total discounted energy-system costs, one can compute a measure of CO_2 mitigation costs as the relative change in in the "zero GERD", "baseline" and "R&D doubling" scenarios relative to the baseline scenario without climate policy. As can be seen, the CO_2 mitigation costs are slightly lower for the "R&D doubling" scenario, substantially lower for the "high R&D", and higher in the zero GERD scenario, as compared to the mitigation costs in the baseline scenario, where R&D spending grows according to the SAPIENTIA R&D outlook (Kouvaritakis, 2005b).

Figure 3-10: CO_2 mitigation costs estimated as the change in the total discounted energy-system costs in the "High R&D", "R&D doubling", baseline and "Zero-GERD" scenarios relative to the baseline scenario without climate policy.



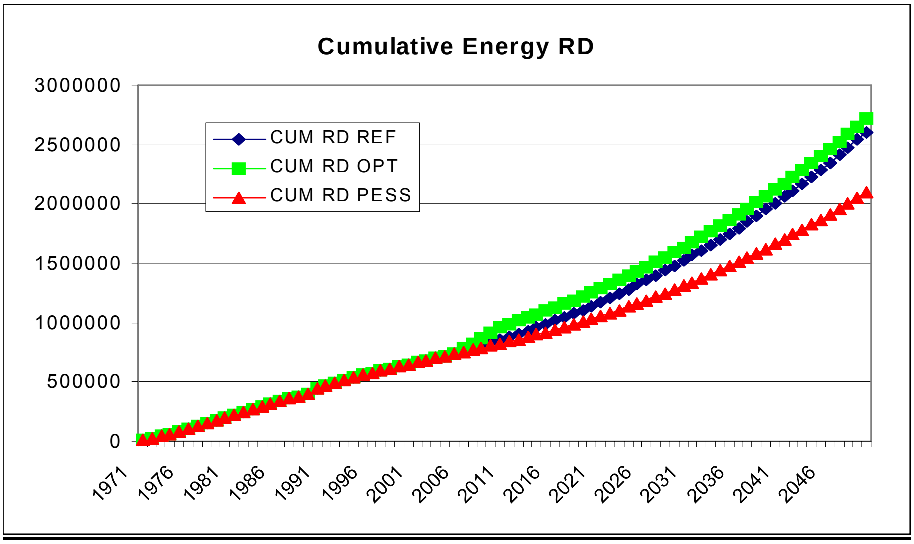
4. POLES Results

The developments of the POLES model in the SAPIENTIA project has been significant as they combined the extension of the time horizon of the simulations from 2030 to 2050, the introduction of new "radical innovation" technologies such as hydrogen and CO_2 Capture and Sequestration and finally the incorporation of full-fledged Two Factor Learning Curves with Clustering effects as defined in the SAPIENTIA project. All these improvements in the model has allowed to perform consistent R&D policy simulations, the results of which have been compared with those of the other models. results

4.1. R&D scenarios implementation in the POLES model

The initial set of R&D scenario as defined in the SAPIENTIA project includes the Reference case, with regularly increasing public R&D budgets, a «Zero GERD» case, with a full stop in public R&D and a «R&D Doubling» case with a doubling of the public R&D effort between 2005 and 2010 (Figure 4-1)

Figure 4-1 World cumulative energy R&D spending scenarios



Source: POLES model, R&D scenarios

4.2. Dynamic impacts of R&D scenarios on power generation technologies

The three R&D scenarios allow to simulate and study the complex dynamic impacts of R&D policies on the development and performance of the different technologies. From the outset it might be expected that all technologies will show lower costs and higher diffusion in the «R&D Doubling» case and conversely higher cost and slower diffusion in the «Zero GERD» case. Of course considerations of inter-technology competition effects are due to make results more complex. This is largely confirmed by the analyses of Table 4-1 , which shows the results of the three scenarios for the investment costs and installed capacities of sixteen key power generation technologies.

4.2.1. Impacts of R&D scenarios on costs and capacities

From these sixteen technologies, only seven display changes from one scenario to the other that confirm the above-mentioned first-order statement on the impacts of R&D. More precisely, the key impacts, as displayed in the two columns identified as “Variation from Reference in 2050” in Table 4-1 can be summarised while analysing first the impacts on investment costs, then those on capacities.

Impacts on total investment costs:

- For all technologies the impacts of different R&D scenarios indeed result in lower cost in the «R&D Doubling» case and higher costs in the «Zero GERD» case.
- However these impacts are significantly different from one technology to the other and also in terms of magnitude from the «R&D Doubling» to the «Zero GERD» case, while it should be reminded here that the «R&D Doubling» and «Zero GERD» cases represent respectively an increase of 4 % and a decrease of 20 % in cumulative R&D in 2050.
- For most new coal-based and renewable-based technologies, the decrease in cost is in the order of -0.5 % in the optimist case, while the increase in the «Zero GERD» case is in the range of +2 to +8 %.
- These impacts are relatively more limited for conventional coal and natural gas technologies.

- The technology that shows the strongest impact is indeed the New Nuclear Design (Gen4) plant, with a cost decrease of 15 % in the «R&D Doubling» case and an increase of 84 % in the «Zero GERD» one.

Table 4-1 Impacts of R&D scenarios on power generation technologies

		Investment cost (€/kWe)				Capacities (Mwe)				*Var. from Ref in 2050*		Total Learning Rate	
		2001	2010	2030	2050	2001	2010	2030	2050	*Costs*	*Capacities*	2010-2030	2030-2050
CCT	**Ref**	1 219	1 190	1 134	1 100	903 975	981 787	657 415	411 977				
	Opt	1 219	1 189	1 133	1 099	903 975	981 277	655 480	409 611	*-0,07%*	*-0,57%*		
	Pess	1 219	1 190	1 134	1 101	903 975	982 105	663 820	423 163	*0,08%*	*2,72%*		
PFC	**Ref**	1 330	1 267	1 124	1 050	12	131 080	839 229	818 214			4,36%	
	Opt	1 330	1 257	1 117	1 046	12	131 152	843 620	812 319	*-0,38%*	*-0,72%*	4,33%	
	Pess	1 330	1 276	1 184	1 139	12	130 910	818 773	803 012	*8,41%*	*-1,86%*	2,81%	
PSS	**Ref**	2 574	2 347	1 993	1 738	0	0	35 417	633 183				3,24%
	Opt	2 574	2 319	1 986	1 738	0	0	35 567	622 683	*0,00%*	*-1,66%*		3,18%
	Pess	2 574	2 357	2 059	1 833	0	0	35 737	632 804	*5,47%*	*-0,06%*		2,77%
ICG	**Ref**	1 436	1 383	1 271	1 198	11	132 814	871 705	868 748			3,07%	
	Opt	1 436	1 372	1 260	1 192	11	133 042	886 039	869 288	*-0,47%*	*0,06%*	3,06%	
	Pess	1 436	1 389	1 312	1 260	11	132 641	842 632	829 790	*5,22%*	*-4,48%*	2,11%	
CGS	**Ref**	2 161	1 919	1 674	1 547	0	135	151 818	965 361			1,34%	2,91%
	Opt	2 161	1 894	1 662	1 542	0	136	153 196	957 571	*-0,31%*	*-0,81%*	1,28%	2,81%
	Pess	2 161	1 927	1 723	1 618	0	135	149 038	941 141	*4,59%*	*-2,51%*	1,10%	2,34%
GGC	**Ref**	548	536	522	516	174 117	804 148	1 426 200	1 072 793			3,29%	
	Opt	548	534	520	515	174 117	804 336	1 442 373	1 070 225	*-0,13%*	*-0,24%*	3,10%	
	Pess	548	536	522	516	174 117	804 391	1 429 586	1 094 670	*0,12%*	*2,04%*	3,19%	
GGS	**Ref**	1 107	1 051	993	886	259	179	9 639	189 919				2,63%
	Opt	1 107	1 046	992	885	259	179	9 538	185 343	*-0,05%*	*-2,41%*		2,63%
	Pess	1 107	1 051	996	888	259	179	9 335	192 186	*0,21%*	*1,19%*		2,60%
HYD	**Ref**	3 227	3 069	2 754	2 487	762 615	826 368	1 026 599	1 190 616			29,25%	37,91%
	Opt	3 227	3 054	2 738	2 478	762 615	826 290	1 025 909	1 189 933	*-0,39%*	*-0,06%*	29,54%	37,24%
	Pess	3 227	3 069	2 755	2 488	762 615	826 385	1 028 185	1 194 268	*0,02%*	*0,31%*	29,04%	37,62%
NUC	**Ref**	2 797	2 466	1 981	1 826	354 556	395 971	813 077	1 569 107			19,04%	8,21%
	Opt	2 797	2 432	1 965	1 822	354 556	396 219	821 993	1 545 915	*-0,24%*	*-1,48%*	18,35%	7,97%
	Pess	2 797	2 494	2 056	1 865	354 556	395 700	789 984	1 618 999	*2,14%*	*3,18%*	17,61%	8,96%
NND	**Ref**	8 555	7 676	5 852	2 696	0	0	0	196 444				2,89%
	Opt	8 555	7 425	5 651	2 303	0	0	0	257 914	*-14,57%*	*31,29%*		3,30%
	Pess	8 555	7 944	7 676	4 964	0	0	0	65 394	*84,14%*	*-66,71%*		1,74%
WND	**Ref**	1 061	966	821	756	23 900	102 443	766 683	2 150 654			5,45%	5,40%
	Opt	1 061	947	811	752	23 900	103 728	788 085	2 160 047	*-0,48%*	*0,44%*	5,16%	5,05%
	Pess	1 061	974	850	784	23 900	101 944	732 066	2 112 057	*3,71%*	*-1,79%*	4,67%	5,15%
WNO	**Ref**	1 901	1 413	984	834	0	13	127 184	958 383			2,69%	5,52%
	Opt	1 901	1 342	968	830	0	14	137 312	961 813	*-0,51%*	*0,36%*	2,43%	5,35%
	Pess	1 901	1 428	1 017	863	0	13	123 136	952 403	*3,53%*	*-0,62%*	2,53%	5,40%
SPP	**Ref**	3 111	2 937	2 473	2 132	0	4	12 378	254 296			1,49%	3,34%
	Opt	3 111	2 882	2 438	2 120	0	4	13 137	255 832	*-0,57%*	*0,60%*	1,44%	3,21%
	Pess	3 111	2 977	2 713	2 413	0	4	10 756	236 060	*13,17%*	*-7,17%*	0,82%	2,60%
DPV	**Ref**	6 385	4 743	2 647	1 856	990	2 087	36 674	757 708			13,15%	7,81%
	Opt	6 385	4 460	2 535	1 838	990	2 099	40 077	786 240	*-0,93%*	*3,77%*	12,43%	7,21%
	Pess	6 385	4 841	2 944	1 982	990	2 083	32 417	683 502	*6,79%*	*-9,79%*	11,80%	8,61%
BF2	**Ref**	2 477	2 286	2 068	1 937	25 695	75 278	140 505	201 837			10,53%	11,75%
	Opt	2 477	2 242	2 044	1 929	25 695	75 712	141 465	201 905	*-0,44%*	*0,03%*	9,73%	10,71%
	Pess	2 477	2 295	2 106	1 975	25 695	75 202	140 047	202 145	*1,96%*	*0,15%*	9,10%	11,44%
BGT	**Ref**	2 195	2 085	1 848	1 676	6	202	86 734	204 801			1,37%	7,57%
	Opt	2 195	2 057	1 827	1 667	6	204	88 233	205 192	*-0,53%*	*0,19%*	1,34%	7,24%
	Pess	2 195	2 107	2 003	1 914	6	200	79 666	188 180	*14,17%*	*-8,12%*	0,58%	3,62%

Source: POLES model, SAPIENTIA Ref, Opt and Pess

Impacts on installed capacities:

- Five of the sixteen technologies show changes in diffusion patterns that are fully opposed to what may be expected, i.e. lower diffusion in the «R&D Doubling» case and the reverse in the «Zero GERD» one. These are: conventional coal, gas in combined cycle, with and without sequestration, large hydro and conventional nuclear. To a large extent these technologies are mature or “installed” technologies, which – due to the already large accumulated experience and capacities (as shown in the central rows of Table 4-1) – benefit less from increased R&D and, on the contrary, are less harmed than new technologies in case of a slowdown in the research effort.

- This is confirmed by the situation of the new renewable and nuclear (Gen4) technologies which indeed behave conformably to the a priori expectations, as they are more sensitive to changes in R&D spending.
- New coal technologies – with and without CCS – indeed display an intermediary profile, as they suffer from reduced R&D in the «Zero GERD» case, but do not clearly benefit of the «R&D Doubling» case, as their diffusion is lower in that case than in the reference. This might be interpreted as a consequence of "cluster effects" as these new technologies are dependent on the development of conventional technologies that suffer from increased competition in the optimist case.

It thus comes out of this analysis that the «Zero GERD» case would significantly hinder the development of new renewable and nuclear technologies and benefit the technologies in place. Conversely the «R&D Doubling» case, even if it corresponds to a proportional increase in current R&D provides a stronger impulse to the new technologies than to existing ones that lose market shares compared with the reference.

4.3. Total Learning Rates, 2010-2030 and 2030-2050

A second stage in the analysis can be performed while analysing the ex post "Total Learning Rate" (TLR), which can be defined as the reduction in the technology cost that is observed with a doubling of installed capacities, when all other factors in technological dynamics including the impact of R&D are also taken into account[23]. The two last columns in Table 4-1 show this TLR for all technologies between 2010 and 2030 and in all cases that can be computed, i.e. with increases in total installed capacities, starting with non-zero values.

With the SAPIENTIA standard "Two Factor Learning Curves + Clustering" specifications used in the POLES model, the TLR seems to be relatively low, at least lower than the learning ratios that are usually considered, in the range of a 5 -15 % reduction for each doubling of capacities. Table 4-1 displays TLR that are in the range of 1 to 4 % for fossil-fuel based technologies and of 1 to 10 % for new renewable technologies.

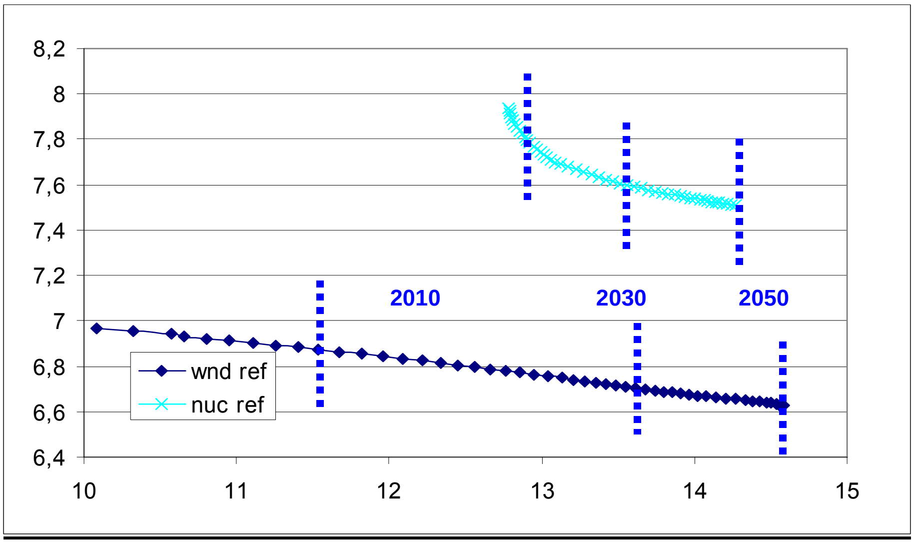
The surprise comes from the "installed" non-fossil technologies – large hydro and conventional nuclear – which show high or very high TLRs, of 30 % or more for hydroelectricity, 20 % during the 2010-2030 period for nuclear. This type of result is indeed largely counter-intuitive as these technologies already benefit both from a significant accumulated knowledge and industrial experience as the installed capacities in 2001 largely testimony.

This can be explained by the fact that limited, but however significant cost reductions (typically of 10 to 20 %) can still be expected from R&D and improved industrial know-how for those technologies, with an increase in capacities that is large in absolute terms, but small in relative terms: for instance nuclear cost is expected to decrease by 20 % between 2010 and 2030, while capacities are multiplied by a factor two (i.e. a TLR of 20 %). Figure 4-2 provides a comparison of the One Factor Learning Curves for conventional nuclear and for wind – to which a load factor of about three should be associated – and illustrates why such differences in TLRs can coexist in what can be considered as a consistent framework.

---

[23] Calculated as: $TLR = 1 - 2\hat{}(Ln[cost_1/cost_0]/Ln[cap_1/cap_0])$

Figure 4-2 One Factor Learning Curves, wind and nuclear (Ln[cost] plotted against Ln[cap])

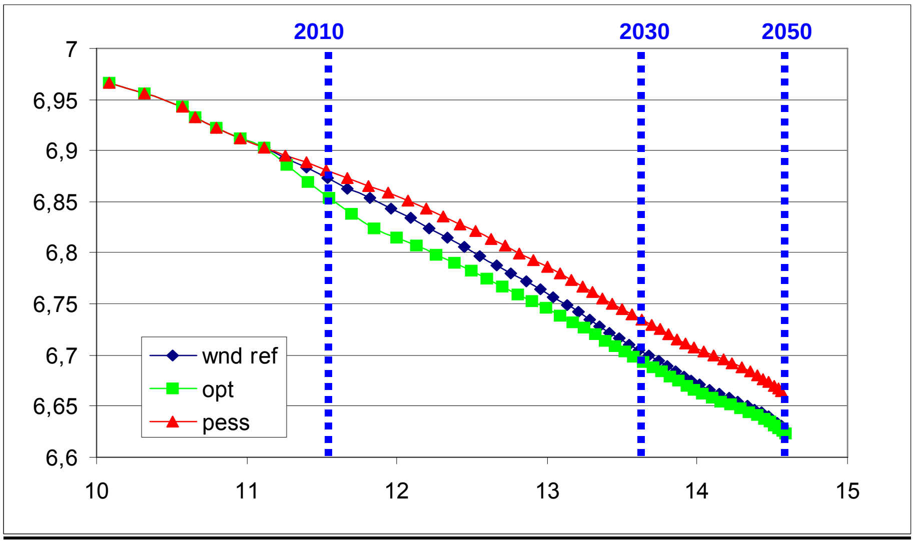


Source : POLES model, R&D scenarios

The analysis of the TLRs in Table 4-1 poses no problem as far as the comparison of the Reference and Pessimist are concerned, as the TLRs are systematically lower in the low R&D scenario: durably lower R&D effort have significant impacts on technology improvement dynamics, as measure by the learning rate.

However the comparison of the Reference and Optimist cases poses more difficulties as the TLR is systematically higher in the former case than in the latter. This is surprising statement as one can expect that the first consequence of an increase in R&D might be an increase in the TLR. A closer look at the learning curve displayed in Figure 4-3, however provides an explanation, which relates to the dynamics of the process over the simulation period.

Figure 4-3: One Factor Learning Curve, wind onshore (Ln[cost] plotted against Ln[cap])



Source: POLES model, R&D scenario

The R&D increase between 2005 and 2010 indeed results in an acceleration of both cost reductions and technology diffusion between 2005 and 2015. However, once this period is passed, the technology dynamics slows down. Due largely to the fact that the cumulative R&D differential decreases in relative terms, by 2030 the Reference cost and diffusion are very similar to those in the Optimist case: the slope of the learning curve between the two arbitrary 2010 and 2030 benchmarks is indeed lower in the Optimist case than in the Reference.

Things are indeed different in the pessimist case, where the growing gap in cumulative R&D compared with the Reference (see above Figure 4-1) also induces a growing gap in cost and installed capacities and thus a durably lower TLR.

4.4. Impacts on Sustainable Development Indicators

The two different R&D scenarios clearly impact the technology dynamics in the model, they also modify in a noticeable way the Sustainable Development (SD) indicators of the SAPIENTIA project that can be assessed with the POLES model. Seven of them have been examined in this study, all of each are considered for their value in 2050:

- cumulative CO_2 emissions,
- recoverable resources/production ratio for oil,
- recoverable resources/production ratio for natural gas,
- world Middle-East dependency ratio,
- the share of low emission vehicle in total traffic,
- the total discounted cost of energy to European consumers,
- the total discounted cost of energy to developing countries' consumers

The results of this exercise show a noticeable impact on each of these indicators (Table 4-2). Although it remains relatively difficult to qualify the sensitivity to the "R&D signal" that is introduced in the model, it appears clearly that an increase of the energy R&D effort has a durable positive impact on the SD indicators. For all indicators the impacts are symmetric and the differential negative impacts of the «Zero GERD» case represent in most cases 2 to 4 times the positive impacts of the «R&D Doubling» one, while the differential in cumulative R&D indeed represents a factor 4 from one scenario to the other.

Table 4-2: Impacts of R&D scenarios on Sustainable Development indicators

2050		REF RD	OPT RD	PESS RD	*opt/ref*	*pess/ref*
Cumulative Total Energy R&D	G€	2 603	2 715	2 095	*4,31%*	*-19,50%*
Cumulative CO2 emissions	GtCO2	1 798	1 795	1 806	*-0,16%*	*0,45%*
Resources / Prod ratio, Oil	yr	36,92	36,95	36,78	*0,09%*	*-0,37%*
Resources / Prod ratio, Gas	yr	32,82	32,85	32,50	*0,11%*	*-0,96%*
Middle-East dependency ratio	%	54,69	54,67	54,78	*-0,05%*	*0,16%*
Share of Low Emission Vehicles	%	60,62	61,95	55,32	*2,18%*	*-8,76%*
Discounted cost of energy to final users (Europe)	G€	30 164	30 137	30 233	*-0,09%*	*0,23%*
Discounted cost of energy to final users (Developing Countries)	G€	38 914	38 858	39 099	*-0,14%*	*0,48%*

Source: POLES model, SAPIENTIA Ref, Opt and Pess

In the «R&D Doubling» case, total cumulative energy R&D in 2050 exceeds that of the Reference case of 112 G€, while it is down of 508 G€ in the «Zero GERD» case. The consequences of these changes in R&D spending can be summarised as follows:

(1) The result in terms of reduction in 2050 CO_2 cumulative emissions is apparently limited. However it represents a decrease of 2.8 $GtCO_2$ in Opt and an increase of 8.2

in Pess. For the «R&D Doubling» case the supplementary spending of 112 G€ thus represent an average reduction cost of 39 €/tCO$_2$, quite a sensible figure.

(2) As far as the oil and gas Resources to Production ratios are concerned, the global impacts are relatively limited. In the case of oil this is largely explained by the fact that the SAPIENTIA Reference projection is already strongly constrained, with an already strong diffusion of low emission vehicles. A more significant change appears for the gas Resource to Production ratio in the «Zero GERD» case, reflecting the fact that natural gas consumption in power generation increases when the diffusion of new renewable and nuclear options is strongly limited.

(3) The oil dependency ratio from the Middle-East and the market share of low emission vehicles is also impacted by the R&D scenarios. This is largely for reasons mentioned above and related to a strong pre-existing constraint on the oil system. Significant changes in the diffusion of low emission vehicles appear however in the «Zero GERD» case, in which the decrease of the R&D effort translates into much lower penetration rates

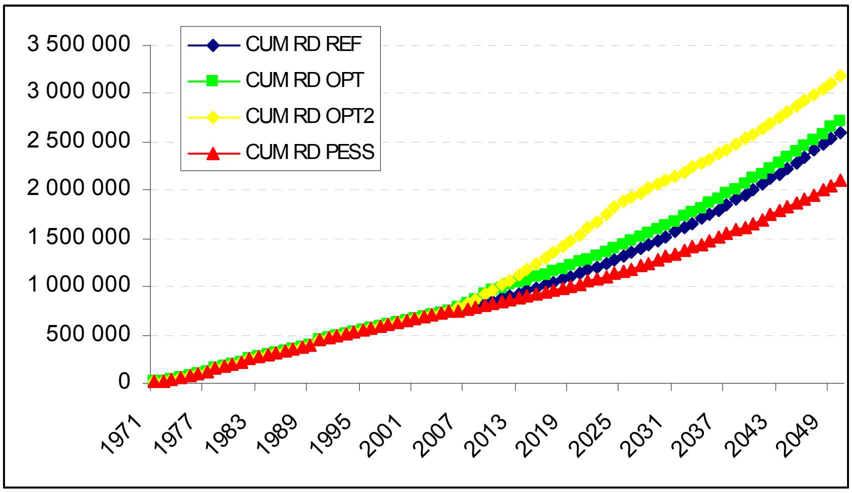
(4) The impact on the total discounted cost of energy for final users in Europe and in the developing countries is limited in relative terms, representing changes below 0.5 % of the energy bill. However when the absolute values are considered and compared to the initial "R&D signal", the orders of magnitude appear highly consistent: for instance the extra 112 G€ spent in the Optimist case result in a discounted reduction of 27 G€ of the energy cost for European end-users and of 56 € for the ones of the developing world. Thus three fourth of the initial "investment" in research may be repaid by long term reductions in the cost of energy of these two sets of countries (representing indeed ¾ of world energy consumption in 2050 (see above Figure 5-6).

4.5. The "High R&D" scenario

The "R&D Doubling" scenario initially defined in SAPIENTIA provides a realistic hypothesis for the increase in R&D effort – i.e. a doubling of total spending during five years. It however came out of the different exercises that in order to provide a balanced comparison with the «Zero GERD» case – which is indeed a very pessimistic one with -20% in cumulative research by the end of the period – it would be instructive to perform a very optimistic case ("High R&D" scenario –or opt2) with a positive shock in cumulative research of a similar magnitude.

This case is simulated through the simple hypothesis of a doubling of public research over the outlook instead of during only 5 years (see Figure 4-4).

Figure 4-4: World cumulative energy R&D spending scenarios



Source: POLES model, R&D scenarios

The results of the very optimistic scenario (OPT2) are illustrated in Table 4-3, which is developed in the same logic as Table 4-1 . The impacts of this new case are of the same nature as those of the initial optimistic case, but they are now significantly amplified. In particular impacts on the total cost are typically five times higher for new clean technologies.

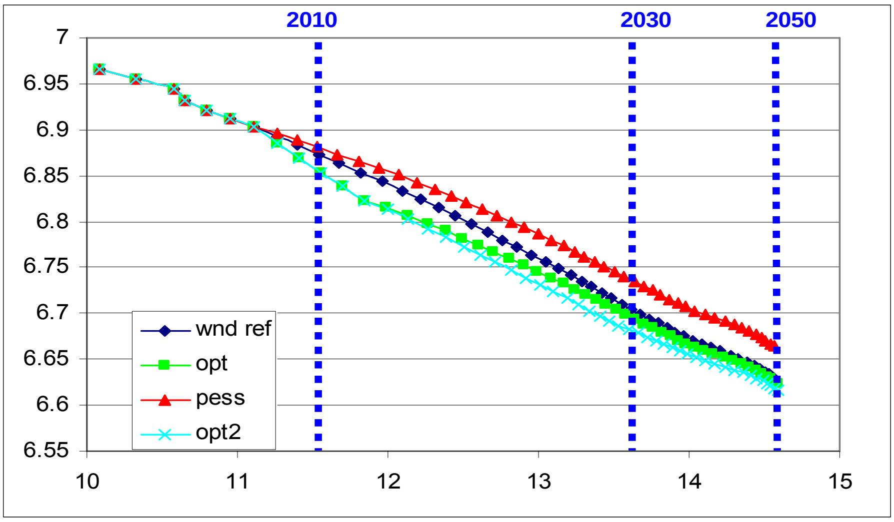
Table 4-3: "High R&D" case OPT2, impacts on power generation technologies

		Investment cost (€/kWe)				Capacities (Mwe)				*Var. from Ref in 2050*		Total Learning Rate	
		2001	**2010**	**2030**	**2050**	**2001**	**2010**	**2030**	**2050**	***Costs***	***Capacities***	**2010-2030**	**2030-2050**
CCT	**Ref**	1 219	1 190	1 134	1 100	903 975	981 787	657 415	411 977				
	Opt2	1 219	1 189	1 129	1 098	903 975	981 203	650 071	394 827	*-0.19%*	*-4.16%*		
	Pess	1 219	1 190	1 134	1 101	903 975	982 105	663 820	423 163	*0.08%*	*2.72%*		
PFC	**Ref**	1 330	1 267	1 124	1 050	12	131 080	839 229	818 214			4.36%	
	Opt2	1 330	1 257	1 089	1 031	12	131 133	842 157	769 303	*-1.81%*	*-5.98%*	5.21%	
	Pess	1 330	1 276	1 184	1 139	12	130 910	818 773	803 012	*8.41%*	*-1.86%*	2.81%	
PSS	**Ref**	2 574	2 347	1 993	1 738	0	0	35 417	633 183				3.24%
	Opt2	2 574	2 336	1 954	1 718	0	0	34 745	563 983	*-1.15%*	*-10.93%*		3.16%
	Pess	2 574	2 357	2 059	1 833	0	0	35 737	632 804	*5.47%*	*-0.06%*		2.77%
ICG	**Ref**	1 436	1 383	1 271	1 198	11	132 814	871 705	868 748			3.07%	
	Opt2	1 436	1 372	1 226	1 172	11	133 023	909 221	842 249	*-2.15%*	*-3.05%*	3.97%	
	Pess	1 436	1 389	1 312	1 260	11	132 641	842 632	829 790	*5.22%*	*-4.48%*	2.11%	
CGS	**Ref**	2 161	1 919	1 674	1 547	0	135	151 818	965 361			1.34%	2.91%
	Opt2	2 161	1 907	1 624	1 519	0	134	153 656	888 229	*-1.78%*	*-7.99%*	1.57%	2.60%
	Pess	2 161	1 927	1 723	1 618	0	135	149 038	941 141	*4.59%*	*-2.51%*	1.10%	2.34%
GGC	**Ref**	548	536	522	516	174 117	804 148	1 426 200	1 072 793			3.29%	
	Opt2	548	534	517	513	174 117	804 172	1 453 377	1 041 731	*-0.54%*	*-2.90%*	3.83%	
	Pess	548	536	522	516	174 117	804 391	1 429 586	1 094 670	*0.12%*	*2.04%*	3.19%	
GGS	**Ref**	1 107	1 051	993	886	259	179	9 639	189 919				2.63%
	Opt2	1 107	1 049	995	883	259	179	7 539	165 202	*-0.30%*	*-13.01%*		2.64%
	Pess	1 107	1 051	996	888	259	179	9 335	192 186	*0.21%*	*1.19%*		2.60%
HYD	**Ref**	3 227	3 069	2 754	2 487	762 615	826 368	1 026 599	1 190 616			29.25%	37.91%
	Opt2	3 227	3 054	2 669	2 437	762 615	826 295	1 023 780	1 186 144	*-2.02%*	*-0.38%*	35.32%	34.80%
	Pess	3 227	3 069	2 755	2 488	762 615	826 385	1 028 185	1 194 268	*0.02%*	*0.31%*	29.04%	37.62%
NUC	**Ref**	2 797	2 466	1 981	1 826	354 556	395 971	813 077	1 569 107			19.04%	8.21%
	Opt2	2 797	2 432	1 929	1 813	354 556	396 193	825 150	1 415 547	*-0.72%*	*-9.79%*	19.69%	7.64%
	Pess	2 797	2 494	2 056	1 865	354 556	395 700	789 984	1 618 999	*2.14%*	*3.18%*	17.61%	8.96%
NND	**Ref**	8 555	7 676	5 852	2 696	0	0	0	196 444				2.89%
	Opt2	8 555	7 425	5 025	2 184	0	0	0	249 755	*-18.98%*	*27.14%*		3.07%
	Pess	8 555	7 944	7 676	4 964	0	0	0	65 394	*84.14%*	*-66.71%*		1.74%
WND	**Ref**	1 061	966	821	756	23 900	102 443	766 683	2 150 654			5.45%	5.40%
	Opt2	1 061	947	782	740	23 900	103 734	828 038	2 151 081	*-2.09%*	*0.02%*	6.19%	3.93%
	Pess	1 061	974	850	784	23 900	101 944	732 066	2 112 057	*3.71%*	*-1.79%*	4.67%	5.15%
WNO	**Ref**	1 901	1 413	984	834	0	13	127 184	958 383			2.69%	5.52%
	Opt2	1 901	1 342	912	812	0	14	145 605	964 062	*-2.58%*	*0.59%*	2.85%	4.15%
	Pess	1 901	1 428	1 017	863	0	13	123 136	952 403	*3.53%*	*-0.62%*	2.53%	5.40%
SPP	**Ref**	3 111	2 937	2 473	2 132	0	4	12 378	254 296			1.49%	3.34%
	Opt2	3 111	2 882	2 301	2 064	0	4	14 878	256 849	*-3.18%*	*1.00%*	1.90%	2.60%
	Pess	3 111	2 977	2 713	2 413	0	4	10 756	236 060	*13.17%*	*-7.17%*	0.82%	2.60%
DPV	**Ref**	6 385	4 743	2 647	1 856	990	2 087	36 674	757 708			13.15%	7.81%
	Opt2	6 385	4 460	2 232	1 783	990	2 099	47 312	823 507	*-3.93%*	*8.68%*	14.27%	5.31%
	Pess	6 385	4 841	2 944	1 982	990	2 083	32 417	683 502	*6.79%*	*-9.79%*	11.80%	8.61%
BF2	**Ref**	2 477	2 286	2 068	1 937	25 695	75 278	140 505	201 837			10.53%	11.75%
	Opt2	2 477	2 242	1 983	1 904	25 695	75 714	142 897	201 356	*-1.71%*	*-0.24%*	12.52%	7.92%
	Pess	2 477	2 295	2 106	1 975	25 695	75 202	140 047	202 145	*1.96%*	*0.15%*	9.10%	11.44%
BGT	**Ref**	2 195	2 085	1 848	1 676	6	202	86 734	204 801			1.37%	7.57%
	Opt2	2 195	2 057	1 752	1 631	6	204	91 267	205 767	*-2.69%*	*0.47%*	1.81%	5.89%
	Pess	2 195	2 107	2 003	1 914	6	200	79 666	188 180	*14.17%*	*-8.12%*	0.58%	3.62%

Source: POLES model, SAPIENTIA Ref, Opt2 and Pess

The indirect and dynamic effects are complex to identify, but one can in particular notice a significant increase in Total Learning Rates for new technologies before 2030 (period in which the increased R&D takes place). This is in particular the case for all renewable technologies, for which the TLR is much higher between 2010 and 2030 than in the initial optimistic case, but slightly lower during the following period, as the bulk of the learning effects have already taken place (see Figure 4-5).

Figure 4-5: One Factor Learning Curve, wind onshore (Ln[cost] plotted against Ln[cap])



Source: POLES model, R&D scenario

The impacts on the sustainable development indicators are also significantly amplified in the very optimistic case and they now represent changes of several percentage points, except for the "heaviest" indicators (total discounted energy costs) (see Table 4-4). The more critical impact is on the diffusion of Low Emission Vehicles that increases from 60 % in the Reference to 75 % in the very optimistic R&D case.

Table 4-4: Impacts of R&D scenarios on Sustainable Development indicators

2050		REF RD	OPT2 RD	PESS RD	*OPT2/REF*	*PESS/REF*
Cumulative Total Energy R&D	G€	2 603	3 181	2 095	*22.21%*	*-19.50%*
Cumulative CO2 emissions	GtCO2	1 798	1 778	1 806	*-1.07%*	*0.45%*
Resources / Prod ratio, Oil	yr	36.92	38.51	36.78	*4.32%*	*-0.37%*
Resources / Prod ratio, Gas	yr	32.82	34.10	32.50	*3.92%*	*-0.96%*
Middle-East dependency ratio	%	54.69	53.26	54.78	*-2.62%*	*0.16%*
Share of Low Emission Vehicles	%	60.62	75.36	55.32	*24.31%*	*-8.76%*
Discounted cost of energy to final users (Europe)	G€	30 164	30 037	30 233	*-0.42%*	*0.23%*
Discounted cost of energy to final users (Developing Countries)	G€	38 914	38 589	39 099	*-0.84%*	*0.48%*

Source: POLES model, SAPIENTIA Ref, Opt2 and Pess

5. TIMES G3

The scenario analysis in the SAPIENTIA project focuses on three different scenarios. The first one is the base case (REF) which includes governmaental R&D expenditure. The second scenario does not include the R&D expenditure by a government (PESS) and the third one includes the doubling of governmental R&D expenditure (OPT). In this study the governmental R&D expenditures aims at developing the technologies, thus decreases the investment cost. All three scenarios have taken a linearly increased CO_2 tax into account. It increases from 10 €/t CO_2 in 2010 to 100 €/t CO_2 in 2050. Population and GDP are taken from /POLES 2001/ for all scenarios. The explicit scenarios' definitions are listed below:

REF (Reference)
R&D expenditures by the government
with CO_2-Tax (linear increase from 10 €/t CO_2 in 2010 to 100 €/t CO_2 in 2050)

PESS (Pessimistic)
Without government R&D
with CO_2-Tax (linear increase from 10 €/t CO_2 in 2010 to 100 €/t CO_2 in 2050)

OPT (Optimistic)
Doubling of government R&D
with CO_2-Tax (linear increase from 10 €/t CO_2 in 2010 to 100 €/t CO_2 in 2050)

5.1. EU25 results

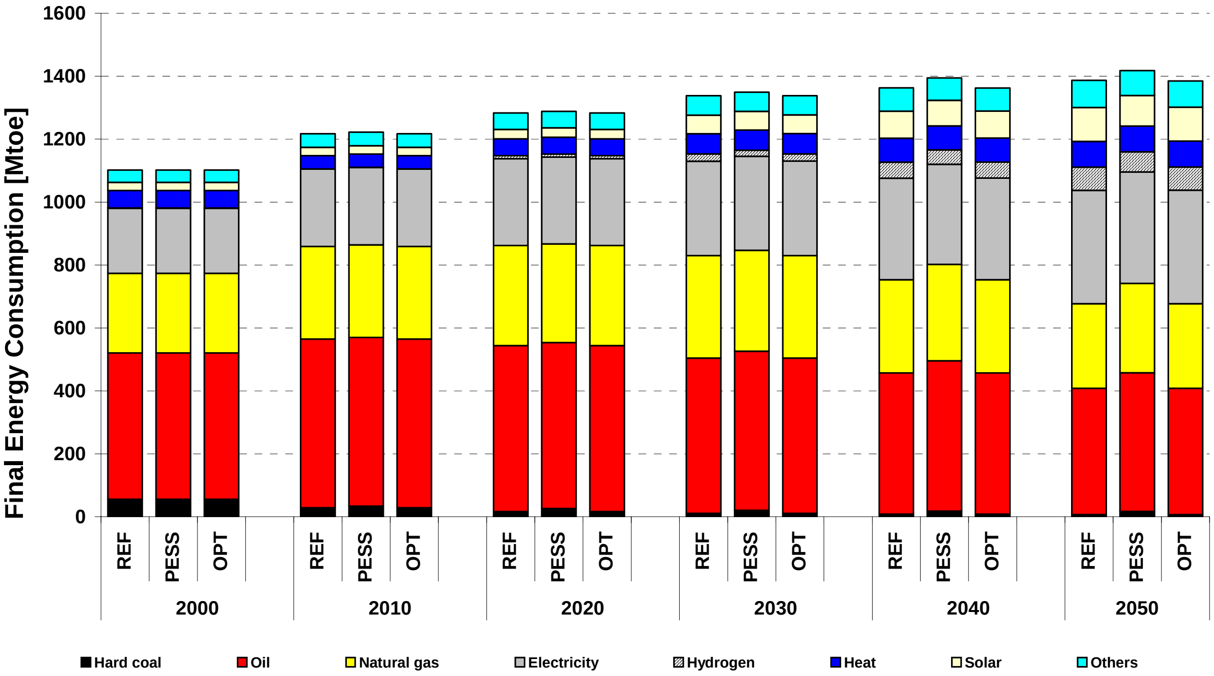
In the following section the focus will be on the results of the EU25 region.

5.1.1. Total Final energy consumption

In the reference case the total final energy consumption follows an increasing trend from the period 2000 to the period 2050 and is about 28% higher in 2050 in compared to 2000. In all scenarios the imposition of CO_2 tax, energy efficiency improvement and saving measures may lead to a reduction in energy demand or fuel switching (from high emission fuels to low emission fuels). For the base case the share of hard coal, oil products and natural gas decreases within the model horizon in the base case. The share of hard coal within the final energy consumption reaches 0.5 % in the year 2050 in compared to 5 % in the year 2000. Likewise the composition of oil products and natural gas drops to 29 % and 19 % in the year 2050 from 42% and 23% in the year 2000. Electricity, solar thermal energy, hydrogen, heat and others increase their share until 2050. Electricity has the highest increase in share of 7.2 % followed by solar thermal energy with 5.4 %, hydrogen 5.3 %, others 2.7 % and finally the slightest increase in share by heat 0.9%.

The consumption of hard coal in the PESS scenario is the highest in compared to the other two scenarios for all model periods, while oil and natural gas do not follow the same pattern like hard coal. The oil consumption in the PESS scenario increases from 2030 and natural gas from 2040 onwards until the final period. In the case of higher R&D expenditures (case REF and OPT compared to case PESS) the penetration of insulation measures and supply efficiency measures (specially condensing boilers and heat pumps) will be much higher. For all periods the total energy consumption in the scenario PESS is above those of the REF and the OPT scenarios. In 2050 the energy consumption of solar (includes also environmental heat) will be in the scenario REF and OPT 10 Mtoe higher than in the scenario PESS. This is due to the increased use of solar heating systems and heat pumps in the commercial, industrial and residential sector.

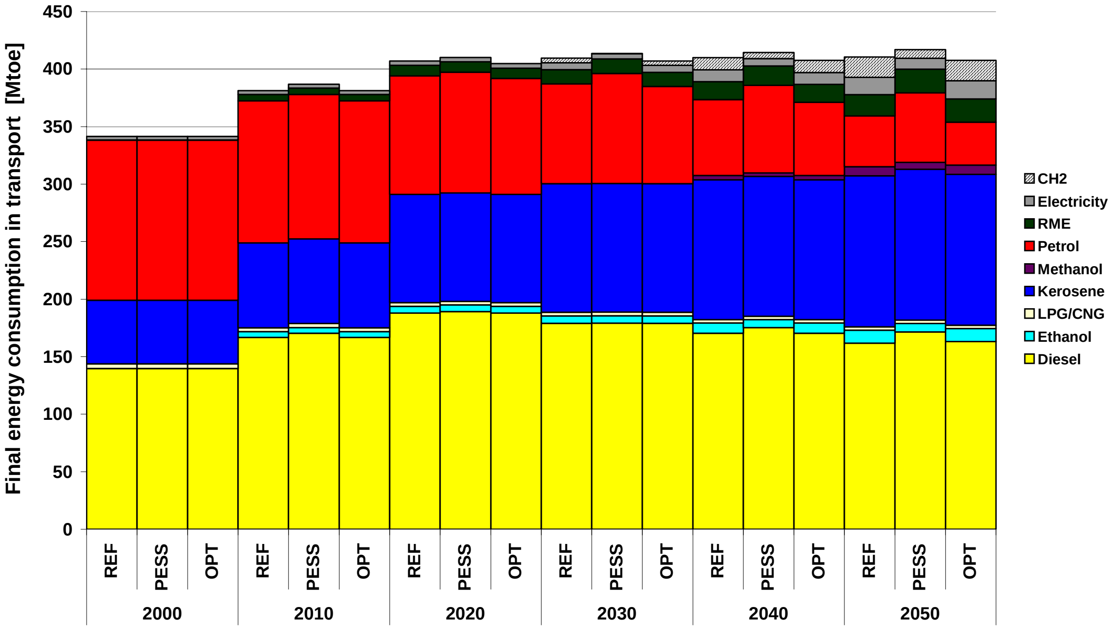
Figure 5-1: Final energy consumption by energy carrier in EU25 [Mtoe]



5.1.2. Final energy consumption in the transport sector

The energy consumption in the transport sector increases from 342 Mtoe in the year 2000 to 417 Mtoe in 2050 with an average growth rate of 0.4 % per year. Generally, among the three scenarios the energy consumption is the highest in the PESS scenario. For some periods the consumption in the OPT scenario is below the REF values, while for certain periods it remains constant. The share of petrol reduces over time due to the shift from gasoline to diesel engines. This is based on the higher efficiency and the lower total costs for car transport. Efficiency improvement of better engines are taken into account. The share of hybrid cars increases significantly, too. Hydrogen is used in the PESS scenario after 2040 while in the REF and OPT scenarios it is taken already in 2030. Due to the R&D expenditure, hydrogen production technologies, hydrogen direct engines and fuel cell cars become economical at an earlier state. The share of diesel in the energy consumption increases until 2030. After 2030 diesel follows a decreasing trend. Ethanol, electricity, RME and kerosene boost their share from the starting until the end period of the model horizon. Ethanol and RME are produced mainly from biomass and natural gas. They increase their share due to the technological advancement. Until 2050 the useful energy demand for air transport grows rapidly. In 2050 25 % of the final energy demand within the transport sector will be needed for air transport. For the nearer future and even until 2050 it is assumed and expected that there will be no alternative fuel concepts developed. In 2050 the final energy demand of the transport sector drops to 29 %, while it has been up to 31 % in the year 2000. The share of kerosene increases in the transport sector as the share of air traffic increases in the modal split. Meanwhile, the share of LPG, CNG and petrol reduces over time. A significant reduction of petrol is observed from the 2000 until 2050, i.e. a decrease down to one eighth of the initial value. Generally, additional R&D expenditures in the scenario OPT have a strong influence to further development of alternative fuels and engine concepts, especially in the public transport sector and in the freight vehicle sector (i.e. heavy trucks).

Figure 5-2:Final energy consumption by energy carrier in the transport sector in EU25 [Mtoe]

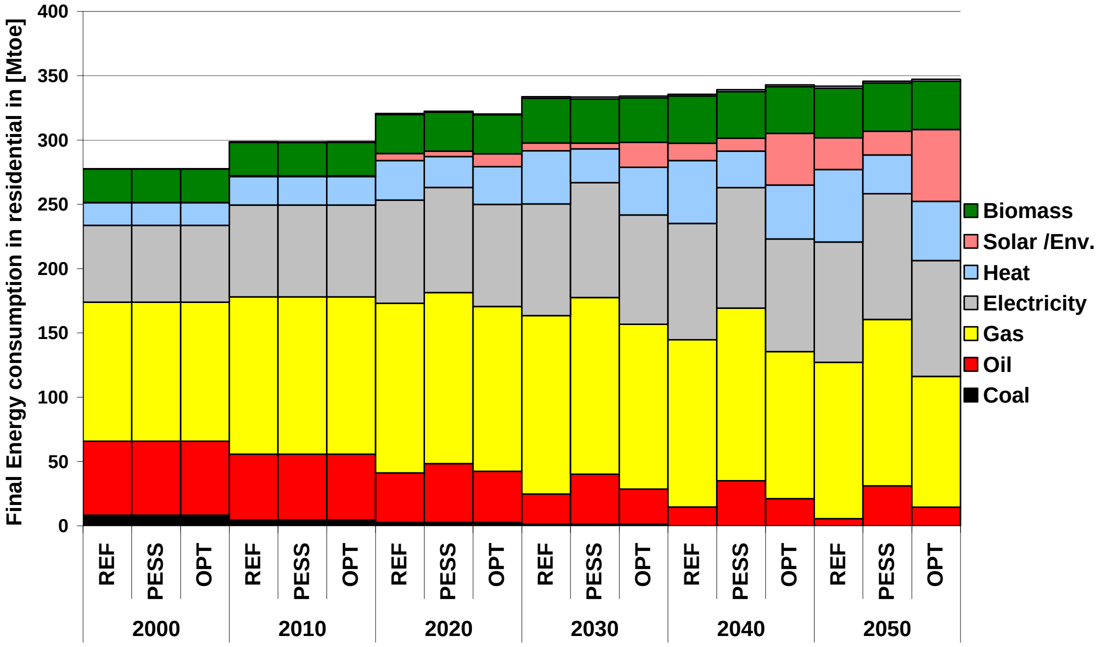


5.1.3. Final energy consumption in the residential sector

The energy consumption in the household sector increases from 278 Mtoe in 2000 to 346 Mtoe in 2050. Thus, the average growth rate is about 0.4 % per annum. In all scenarios measurements for reducing the space heating, which represents the major heat demand in the household sector of the EU25. These measures have been considered based on insulation of the walls, roof of the buildings and enhanced isolation of windows. These saving measures will all be realised within the existing renovation circle of buildings instead of applying them as additional and separate measurements.

Within the total energy consumption the share of hard coal and oil diminishes and hard coal loses its role in the fuel mix after 2040. The contribution of gas within the fuel mix increases until 2030 and follows a diminishing trend towards the final periods. Meanwhile, the share of electricity, heat, solar energy, biomass and geothermal energy increases in the total fuel mix. The use of biomass, especially those of wood pellets boilers, increase over time and will be mainly influenced by the development of CO_2-Certificate prices. Solar energy and environmental heat diffuses heavily followed by geothermal energy towards the end period of the model horizon. This is due to the reduction of the investment cost by R&D expenditure for solar heat collectors and heat pumps. In particular the use of heat pumps reduces the final energy consumption of gas in 2050 even though the total installed capacity of condensing boilers will be higher. The increased use of local and district heating devices in the residential sector is mainly influenced by the CO_2- certificate prices and by the higher R&D expenditures for developing of gas and steam turbines in the scenario REF and OPT.

Figure 5-3: Final energy consumption by energy carrier in residential sector in EU25 [Mtoe]



5.1.4. Net electricity generation

The overall electricity production increases from 2412 TWh in 2000 to 4659 TWh in the scenario PESS in 2050 or around 4630 TWh in the scenario REF and OPT, which represents an increase of almost 70 %. In all scenarios the shares of nuclear, oil and hydro decrease towards the final periods, while other energy carriers increase their share. After 2030 there is negligible electricity production based on oil power plants.

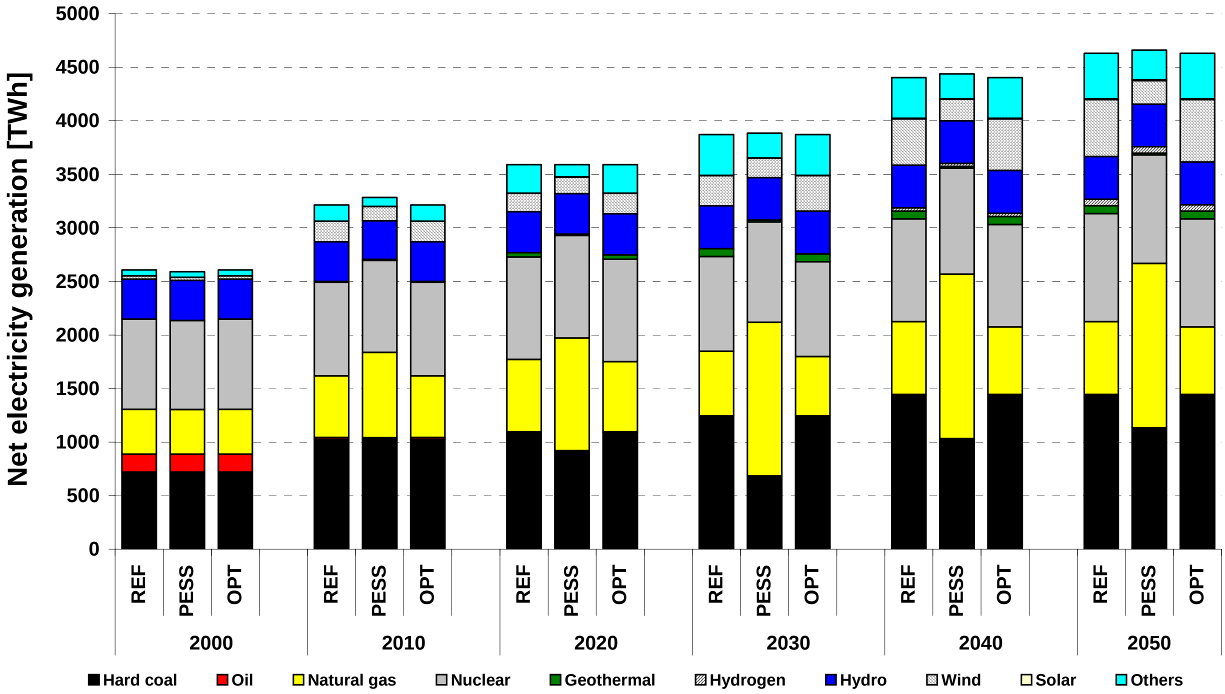
The electricity generation in nuclear power plants is restricted to a certain range, due to the phase out in some EU-25 countries and the grid restricted possibility of electricity exchange between the countries in all scenarios. With the given CO_2-Certificate prices the maximum possible electricity generation by nuclear will be fulfilled in all three scenarios.

The share of electricity generation based on natural gas increases specifically in the scenario PESS. In the other scenarios the combination between public R&D expenditures and CO_2-taxes have an influence on the cost efficiency of CO_2 capture and storage technologies especially in combination with the implementation of coal IGCC power plants. Hence, the share of electricity generation based on coal increases to a level of around 31.2 % in the scenarios REF and OPT.

Hydrogen will be used for storing electricity produced by fluctuating electricity generation, especially by those of future wind power plants. In parallel the public R&D expenditures assist the hydrogen based technologies in the consumption sector. Even though the electricity production from hydrogen still takes only a marginal share towards the final periods. For years geothermal power plants have been used in Italy for generating electricity. The investment of public R&D will speed up the reduction of the specific investment costs of HDR plants. The increase of electricity generation based on Photovoltaic (PV) is more or less scenario independent.

Based on the higher share of R&D in scenario OPT the specific cost reduction of wind mills decreases faster than in the other scenarios until 2050. Due to the lower investment cost in the scenario OPT wind power plants will generate 582 TWh in compared to only approx. 225 TWh in scenario PESS in the year 2050.

Figure 5-4: Net electricity generation by energy carriers in EU25 [TWh]



5.1.5. Net electricity generation capacity

The net electricity generation capacities in the different scenarios corresponds to the net electricity generation in the different scenarios.

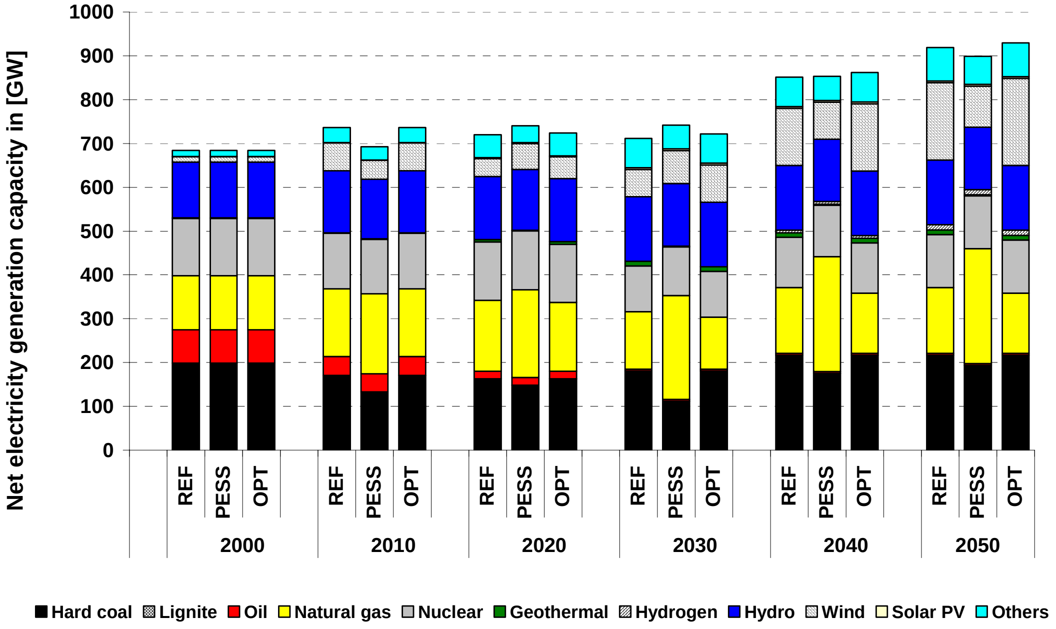
The electricity generation capacity of the EU25 increases from 634 GW in 2000 up to 899 GW in the scenario PESS in 2050, which represents an increase of around 31 %.In the scenario PESS the major share by coal (25%) in the year 2000 is replaced by natural gas (29%) in the year 2050. Within this time frame the share of coal, nuclear, oil and hydropower declines by 4 %, 7 %, 11 % and 4 % respectively. Whereas natural gas, wind, PV, geothermal, hydrogen and others all enlarge their shares by 10 %, 8 %, 0.4%, 0.1%, 1 % and 5 % respectively. The total capacity of nuclear reaches 121 GW in the year 2050, independently from the analyzed scenario.

Based on the higher amount of R&D expenditure in scenario OPT in the year 2050 approx. 200 GW (93 GW in PESS) wind power plants and 11 GW (2 GW in PESS) of geothermal power plants will be installed.

The installed net electricity generation capacity of gas in 2050 differs mainly between the scenario PESS with 262 GW and the scenario OPT with 137 GW, while the capacity differences of coal are negligible (197 GW in the scenario OPT and 194 GW in the scenario PESS in the year 2050).

Based on the uncertainty of the availability especially of wind power plants the total installed capacity in the scenario REF and OPT is higher than in the PESS scenario. Additionally, based on the lower availability of the wind power plants and the lower utilization of CHP plants the total capacity in these both scenarios is higher. The capacity of the OPT scenario is higher in compared to the other scenarios after the year 2030.

Figure 5-5: Net electricity generation capacity by energy carriers in EU25 [GW]



5.1.6. Influence on sustainability indicators and other indicators

The total primary energy consumption in the EU25 increases from 1668 Mtoe in 2000 to 1923 Mtoe in the scenario PESS and to 1830 Mtoe in scenario OPT in the year 2050 In the primary energy fuel mix hard coal, nuclear, hydro and oil reduce their share towards the final period.

The ratio of fossil to nuclear within the total primary energy consumption is the lowest in the PESS scenario. The ratiois significantly higher in the other two scenarios (REF, OPT) as the policy of nuclear phase out has been implemented.

In each period, the penetration of renewable technologies advances when R&D investments are carried out. Compared with the share of the year 2000 the ratio between renewable and fossil primary energy consumption will be three times higher in 2050 in the scenario OPT while iti is approx. only two times higher in the scenario PESS. This can be seen as an indicator that investment on R&D will influence a higher degree of sustainability in the energy system.

The import of grid connected natural gas in the EU25 energy system is lower in the REF and OPT scenario in compared to PESS. After 2030 the import dependence shows a significant increase due to emptiness of extracted gas fields in Europe. The import dependence of grid connected gas in the scenario OPT until 2050 is lower than in the other scenarios. In the year 2050 the import dependency in all scenarios is one, because no more gas resources and reserves are available in Europe. In the scenario OPT the availability of the gas reserves and resources can be extended by spending more money on R&D and will therefore contribute to a more sustainable development.

The total gas consumption is increasing to 63 % in the scenario PESS compared to 10 % in the scenario OPT in the year 2050. In this case an additional amount of 174 Mtoe gas have to be imported into the EU 25. On the other hand, only 59 Mtoe more coal will be consumed in the scenario OPT in compared to the scenario PESS. Thus, the import dependence of fossil fuels will increase a lot more without spending more money R&D. Regarding the aspect of sustainability this implies a less fossil fuel dependent energy system.

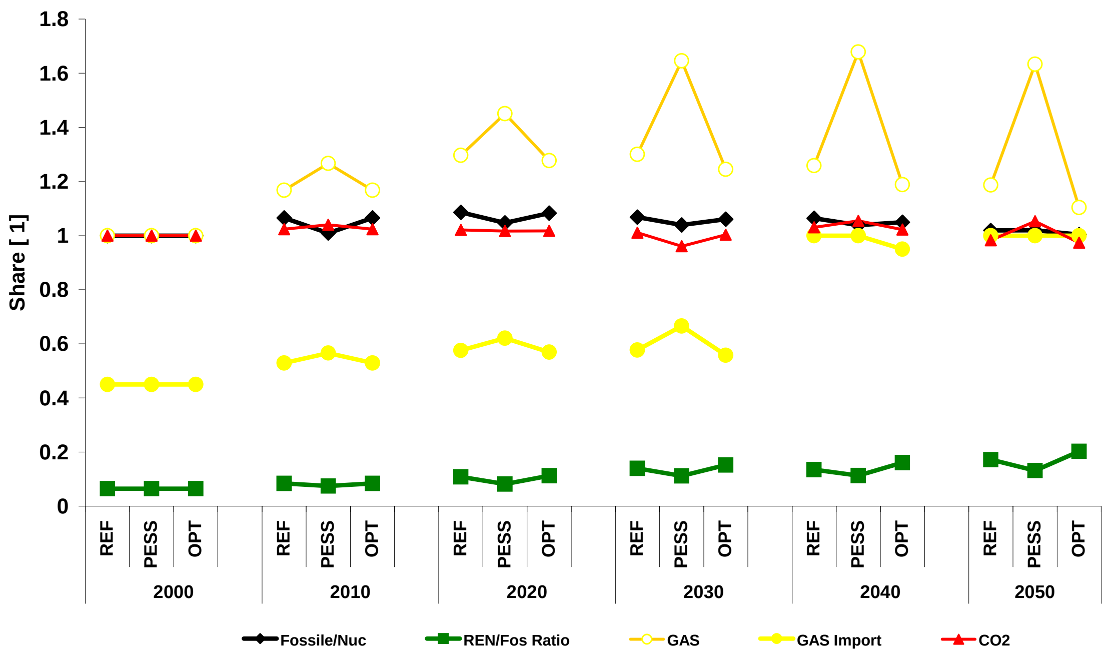
The carbon dioxide emission in the PESS increase by only 5% towards 2050 compared with the year 2000..In the other both scenarios with public R&D investment will lead to a

CO_2 decrease of around 2 to 3 % until 2050. Concerning the sustainability criteria the energy system in scenario OPT reaches a significantly higher state than the scenario PESS.

In all scenarios the carbon tax has a major influence on the reduction of CO_2 emissions. In the EU25 more renewable and less carbon intensive energy carriers intermingled the energy systems structure, especially considering so the marginal emission growth in compared to the significant increase in energy demand. Additionally, the energy efficiency ratio increases from 0.66 in 2000 to 0.74 in 2050 in the PESS scenario but in the case of R&D investment, it increases from 0.66 in 2000 to 0.77 in 2050.

Scenarios with enhanced R&D policy are able to implement advanced fossil fuel based technologies, which have lower emissions due to the combination of CO_2 sequestration and capture technology.

Figure 5-6: Share of different indicators in the EU25 [Mtoe]



5.2. Conclusion

The study analyses the transition of technological mix, fuel mix and it's interplay inside an energy system by the introduction of an R&D fund especially modelled inside TIMES. These R&D expenditures are responsible for the reduction of investment cost of the technology. Although the technological transformation depends upon many factors like, techno-economic parameter, R&D investment, social acceptance, diffusion and production rate, still R&D has a significant effect on it. Continuous R&D expenditure for alternative fuels and engines leads to efficiency improvement concepts which increase the share of alternative modes to of over 50 % of the total individual transport. The introduction of condensing boilers; heat pumps; district and local heating (CHP based), saving measures of electricity and carbon dioxide tax do not only reduce Green House Gas (GHG) emission to a great extent but also reduce the final energy demand in each sector. Hydrogen enters into the transport sector towards the middle period of the planning horizon and is used in stationary applications for electricity production, which indirectly improves the grid stabilisation. R&D expenditure and technological improvement guided the more compatible energy system. R&D for Carbon Capture and Storage (CCS) speeds up the flexibility of the power under emission reduction target, i.e. the selection of bigger units of gasification selects the gasification unit of power production for electricity and heat generation. The R&D expenditure has an impact on the development of different sustainability indicators like fossil/nuclear, renewable/fossil ratio, utilisation of gas, gas import and CO_2 production. All these indicators changed their values by the introduction of R&D and it’s behaviour is recognised by comparing the values the initial ones. The results shows that public R&D for energy supply and demand technologies will influence future energy systems to a more sustainable development.

After all, the optimal integration of technologies in future energy systems and the intelligent solution will remain a constant challenge.

References

/Adelman 1993/Adelman, M.A. 1993. Modelling World Oil Supply. In: Adelman, M.A.: The Economics of Petroleum Supply. The MIT Press. Cambridge, Massachussets.

/Barreto 2001/ Barreto l., (2001).” Technological Learning in Energy Optimisation Models and Deployment of Emerging Technologies”, Diss. ETH Nr 14151, pp 52, 53, 105, 129.

/BP 2004/BP Statistical Review of World Energy, BP, London, pp. 6-30, 2004.

/Cedigaz 2004/Cedigaz (2004), Natural Gas in the World, Institut Français du Pètrole Rueil-Malmaison.

/DeLuca 1998/DeLuca, M. 1998. Drilling Cost per foot is up as cost per barrel declines. Offshore Magazine. January 1, 1998.

/DOE/EIA 2004/International Energy Outlook, DOE/EIA-0484, pp.36-76, 2004.

/DOE/EIA 2001/Energy Information Administration, International Energy Agency 2001, DOE/EIA-0219(2001) (Washington, DC, February 2003), Table 8.2.

/ETSAP 2002/Energy Technology Systems Analysis Programme (ETSAP).: International Energy Agency Energy Technology Systems Analysis Programme: Contributing to the Kyoto Protocol, Summary of Annex VII (1999-2002), 2002.

/Goldstein, Greening 2001/Goldstein, G.A., Greening L.A. (2001) Energy Planning and the development of carbon mitigation strategies-Using the MARKAL family of models, (available under http://www.ecn.nl/unit_bs/etsap/reports/markal.html).

/hm-usa/http://www.hm-usa.com/distance/usa.html

/IPCC 2001/ Climate Change 2001: The scientific Basis. Intergovernmental Panel on Climate Change, Third Assessment Report, Working Group I. Cambridge University Press. P.944.

/Loulou et al. 2005/Loulou R., Remne U., Lehtila A., Goldstein G., “Documentation for the TIMES Model, PART II,” April 2005, Energy Technology Systems Analysis Programme, http://www.etsap.org/tools.htm.

/Nordhaus and Boyer 2001/Nordhaus W.D. and Boyer J., (1999), Roll the DICE again: Economic models of global warming, Yale University.

/OPEC 2003/Annual Statistical Bulletin 2003, Petroleum Exporting Countries (OPEC), Vienna.

/Remme et al. 2001/Remme, U., Goldstein, G., Schlenzig, C., und Schellmann, U.: MESAP/TIMES Advanced decision support for energy and environmental planning. In P. Chamoni und R. Leisten (Hrsg.), Operations Research Proceedings 2001, S. 59-66, Springer-Verlag, Berlin, 2001.

/Rogner 1997/Rogner, H.H. 1997. An assessment of world hydrocarbon resources. Annual Review of Energy and Environment, 22:217-262.

/SAUNER 2000/SAUNER “Sustainable And the Use of Non-rEnewable Resources”, Cntract ENV4-CT97-0692, EU DGXII Environment and Climate Programme, Final Report November 2000.

/SSB ISY 1999/International Statistical Yearbook, 1999.

/USGS 2000/World Petroleum Assessment 2000, United States Geological Survey (USGS), Washington.

/usembmal/http://usembassymalaysia.org.my/distance.html

/USA.mining-1980/U.S., Bureau of Mines and U.S. Geological Survey (1980). Principles of a Resource/reserve Classification for Minerals. U.S. Geological Survey Circular 831.

/Voort et al. 1984/Van der Voort, E., Doni, E. et. al. (1984) EFOM-12C Mark I, Energy Supply Modelling Package, Mathematical Description, Rapport 8896.)

/Wigley and Raper 2001/T.M.L. Wigley, S.C.B. Raper, Science 293, 451 (2001).

/World Oil/World oil, various issues, Gulf Publishing Company, Houston.

/WEC 2003/World Energy Council (WEC) (2003), Survey of Energy Resources, WEC, London.

/Wigley and Raper 2001/T.M.L. Wigley, S.C.B. Raper, Science 293, 451 (2001).

6. PROMETHEUS Results

6.1. Impact of Scenarios on Technology Performance

The following table presents some PROMETHEUS results on the technological impact of the “High R&D” and “Zero GERD” scenarios.

Table 6-1: Impacts on learning and competition between technologies (Source: PROMETHEUS)

Technologies	Investment Cost (% Change from Baseline in 2050)		Capacities (% Change from Baseline in 2050)	
	High R&D	**Zero GERD**	**High R&D**	**Zero GERD**
Coal Conventional Thermal	-0.2	0.0	-6.1	10.9
Supercritical Pulverised Coal	-1.8	8.8	-4.1	-5.5
Pressurized Supercritical with Sequestration	-1.8	8.5	-0.7	-1.0
Integrated Coal Gasification	-2.2	4.7	-3.2	5.9
Gas Tyrbine Combined Cycle	-0.9	0.1	-2.7	8.3
Nuclear (2nd and 3d gen.)	-2.5	5.8	-5.7	6.0
New Nuclear (4th gen.)	-12.0	124	47.3	-85
Wind Turbines Onshore	-2.4	2.9	-3.7	10.7
Solar Thermal Power Plant	-3.1	12.2	1.6	-24.4
Biomass Thermal	-0.3	2.4	-8.4	16.1
Biomass Gasification plus Combined Cycle	-2.6	14.4	-2.6	-18.2
Building Integrated PV	-6.4	5.6	35.6	-6.1

According to PROMETHEUS results fourth generation nuclear power appears to be the broad option that is most sensitive to R&D funding. In the zero GERD scenario PROMETHEUS indicates double costs in 2050 for this technology and possible failure to penetrate the market. On the other hand, in the High R&D case it ends up with a capacity that is considerably (nearly 50 percent) higher than the reference case. These effects are dominant and affect many other technological options (including clean coal, conventional nuclear and some renewable options) that experience crowding out effects, though their costs and efficiencies do improve. The demise of fourth generation nuclear in the Government R&D elimination scenario favours a number of technological options (conventional coal and some gas-based technologies), but most notably conventional nuclear, which registers considerable gains in capacity (6 percent increase) despite receiving lower funding.

Table 6-2: Impact of scenarios on non conventional vehicles and Fuel Cells (Source PROMETHEUS)

	% share in total stock (2050)									**% change from Baseline (2050)**	
	Europe			**Rest of OECD**			**Rest of the World**			**Engine Cost**	
	Baseline	**Zero GERD**	**High R&D**	**Baseline**	**Zero GERD**	**High R&D**	**Baseline**	**Zero GERD**	**High R&D**	**Zero GERD**	**High R&D**
Fuel Cell Vehicle	5.0	2.4	19.0	4.6	2.1	17.1	4.4	2.0	16.6	*46.4*	*-38.0*
H2 Internal Combustion Engine	8.2	8.8	6.5	7.0	7.4	5.7	4.2	4.4	3.4	*-0.3*	*1.0*
Hybrid Vehicle	36.8	36.3	33.0	36.4	35.9	33.1	32.3	32.0	29.5	*0.9*	*-1.4*
Electric Vehicle	5.7	5.4	5.3	3.6	3.4	3.5	6.1	5.7	5.8	*1.7*	*-1.0*
Total non conventional	55.8	52.9	63.9	51.6	48.9	59.4	46.9	44.2	55.3		

	Investment Cost (% Change from Baseline in 2050)	**Capacities** (% Change from Baseline in 2050)
Fuel Cells		
High R&D	*-42.9*	*53.1*
Zero GERD	*32.8*	*-10.1*

Fuel Cells are particularly influenced by the R&D scenarios. They end up with double costs and substantially lower capacities in the zero GERD case, but display double capacity in the “High R&D” scenario. Contrary to their limited prospects in the baseline (where they fail to gain any significant market share), the “High R&D” scenario has resulted in sufficient improvements to their technical and economic performance, taking them beyond “niche” markets. Particularly, in the case of Fuel Cell cars PROMETHEUS results imply virtually no penetration, while the High R&D scenario produces shares in the vehicle stock of around 15 to 20 percent by 2050, by which time fuel cell cars would gain 25 to 30 percent of total new registrations. In fact, in the High R&D scenario other non-conventional vehicles such as Hydrogen Internal Combustion Engine, Hybrid and pure Electric vehicles, though registering improved cost and technical performance, end up with lower shares than in the reference case due to crowding out from the success of Fuel Cell cars. Photovoltaics, being a relatively R&D dependent and fast learning technology, also register gains in capacity in the High R&D case, as simulated by PROMETHEUS.

Such shifts to alternative technological development paths also have implications for sustainable development. The following section examines the impacts of the scenarios on indicators of sustainable development.

6.2. Impact of Scenarios on Sustainable Development Policy Objectives

The table below presents the PROMETHEUS results on the impacts of the alternative R&D scenarios relative to the baseline, with respect to nine SD indicators.

Table 6-3: Comparison of R&D Scenarios with Baseline (in 2050)

SD INDICATORS (2050)		High R&D	Zero GERD
Cumulative CO2 Emissions	*(% Change)*	-0.9	0.5
Atmospheric CO2 Concentration	*(% Change)*	-0.4	0.2
Global Temperature Change (2065 Commitment) °C	*(Δ° C)*	-0.008	0.006
Highest temperature change per decade 2000-2050 °C	*(Δ° C)*	-0.002	0.001
Oil Resources/Production Ratio	*(Δyr)*	8.5	-2.8
Gas Resources/Production Ratio	*(Δyr)*	-2.7	-2.8
Share of Low Emission Vehicles	*(Change in Share)*	8.2	-2.8
Discounted Cost of Energy to Final Users (Europe)	*(% Change)*	-2.2	0.7
Discounted Cost of Energy to Final Users (LDCs)	*(% Change)*	-3.2	1.5

In terms of cumulative CO_2 emissions and atmospheric CO_2 concentration the results from PROMETHEUS indicate relatively limited impacts in both the “High R&D” and “Zero GERD” scenarios. Regarding the former, the reductions in energy-related CO_2 emissions over the 2050 horizon in the “High R&D” case equal to almost 0.9 percent whereas the elimination of government energy R&D results in increases in emissions of about 0.5 percent. The “High R&D” scenario produces reductions in CO_2 atmospheric concentrations by 0.4% whereas the “Zero GERD” scenario also results in moderate increases (0.2%).

Committed global temperature in 2050 (including a 15-year commitment period) is reduced by 0.008°C (relative to 2000) in the “High R&D” scenario and increased by 0.006°C in the “Zero GERD”. As regards the highest temperature change in any one decade of the forecasting period, the former scenario suggests a maximum decrease of 0.002°C/decade while the latter case indicates an increase of up to 0.001°C/decade.

According to the PROMETHEUS results, the impacts of the scenarios on the indicators of security of energy supply are stronger. Under the R&D intensive outlook as implied by the “High R&D” scenario, the resources to production ratio for oil is extended by 8.5 years, indicating an important reduction in vulnerability to oil supply disruptions. On the other hand, the withdrawal of public energy-related R&D support throughout the outlook leads to a reduction in the oil r/p ratio by up to three years. In both the “High R&D” and the “Zero GERD” scenarios PROMETHEUS indicates a reduction to the gas r/p ratio by up to three years; this can be mostly attributed to the considerable uncertainty surrounding the amount of gas that is yet to be discovered.

The “High R&D” scenario implies substantially increased market penetration rates (8 percent increase) for low emission vehicles, whereas the elimination of government R&D strongly hinders their diffusion (3 percent reduction).

Of particular interest for the R&D scenario analysis are the impacts in terms of energy cost reduction to consumers in Europe and Less Developed regions. The impacts for the “High R&D” case represent reductions of about 2.2% for the European consumers and 3.2% for the consumers in developing countries, while the increases for the zero GERD case equal to about 0.7 percent for the former region and 1.5 percent for the latter. The energy cost reductions as implied by the upper range of the “High R&D” case indicate that the initial investment in research is more than covered by the long term reductions in the cost of energy to the consumers in these two regions.

The general consensus arising from the analysis is that the impact of R&D on more traditional objectives is strong but may appear limited for some of the SD targets, despite copious efforts to endogenise as much learning (historical and future) as possible. This outcome arises from three broad categories of reasons, namely the enormity of the issues associated with most of the SD objectives, the existence of ‘built-in stabilisers’ in model structures and baseline assumptions, and finally from problems of targeting of R&D effort. A number of factors operate to mitigate the impacts of R&D scenarios. Key among them is that learning as modelled tends to slow down as the technical possibilities of improvement are exhausted. Also, reductions in costs of energy services that can be attributed to their increased overall efficiency could also potentially encourage their use. Secondary effects on prices play a significant role: reductions in consumption may also lead to lower prices. Inter-option competition tends to neutralise some of the impacts.

All the above caveats notwithstanding, the analysis has demonstrated that the benefits arising on some of the objectives are sufficiently large to more than cover the costs of the policy.

III. Standardised R&D and D&D Shocks

Nikos Kouvaritakis and Vagelis Panos	ICCS-NTUA
Hal Turton	IIASA
Leonardo Barreto and Socrates Kypreos	PSI
K. Smekens	ECN

1. Introduction

Standardised R&D and D&D shocks were basically performed in order to provide the essential numerical input for the ISPA meta-model, the policy integration tool that is used to carry out policy exploration. Since ISPA is specified as an R&D portfolio exploration tool involving hedging the stochastic properties of R&D infusions had to be examined alongside expected impacts. The provision of essential input to the ISPA tool apart, the R&D shock exercises provide useful insights on the comparative productivity of R&D on specific technological options as it emerges from model results and given the R&D objectives retained in the SAPIENTIA project. Since the impact of R&D expenditure on specific technologies is stochastic, this input takes the form of joint probability distributions of the productivity of R&D expenditure on individual technologies in terms of each of the objectives under consideration. The shocks took the form of standardised increases on R&D for each technology.

The main vehicle of transmission from the R&D shock to a desirable effect on the indicator is the R&D term of the Two Factor Learning Curve, variants of which have been incorporated in all models participating in the project. For most models the exercises were limited to shocks of 10% of cumulative R&D on specific technological options (an exception was made for PROMETHEUS where non-linearities were examined by varying the size of the shock – see below). The shocks were applied orthogonally (i.e. affecting one technology at a time) at the beginning of the forecast horizon. Each modelling team has performed a full model sensitivity run for each technology considered. Each one of those runs has produced a new set of values for the different objectives thus telescoping the whole model mechanism linking the TFLC of that particular technology to the impact of the sustainable development indicator representing that objective.

2. ERIS Results

We now examine the impact of energy-related R&D and D&D investment on indicators of sustainability, focusing on climate change and security of energy supply. R&D investment is assumed to contribute to the development of new technologies and the improvement of some existing technologies. However, it should be emphasised that the process of technological change is highly uncertain, and so our analysis of the impact of R&D support programs can only provide a guide in terms of the impact of particular investment strategies. In this analysis, the impact of R&D on the development of a particular technology is assumed to manifest as a decrease in the cost deploying that technology, and possibly related technologies. This may accelerate commercialisation of a new technology, or improve the competitiveness of an existing technology, facilitating more extensive deployment.

We also examine the impact of demonstration and deployment (D&D) programs, which contribute to the accumulation of valuable experience with a particular technology in the marketplace. For instance, a successful introduction of a technology in niche markets can contribute to build up the confidence of potential users, equipment manufacturers and other social actors, such as policy makers. As a result of this experience, the technology performance and/or cost may improve, and these improvements may spillover to related technologies (see Turton and Barreto 2003 and Kouvaritakis and Panos 2005 for a discussion of the implementation of the clusters approach to learning). Accordingly, strategic management of niche markets, where the technology may be attractive due to specific advantages or particular applications, may be important for stimulating the diffusion process of a given technology or cluster of related and/or complementary technologies (Kemp 1997).

For the evaluation of the impacts of R&D and D&D programs we apply the notion of "shocks", i.e., one-off incremental investments in either research and development, or demonstration and deployment at the beginning of the time horizon (the year 2000). However, we treat these two shocks slightly differently to account for how R&D or D&D shocks are most likely and practicably implemented. Specifically, deployment and demonstration shocks are assumed to result in the installation of new and additional capacity of an entire technology (for example, a combined cycle gas turbine power station), which may comprise several independent components (such as a gas turbine, steam turbine and recovery boiler). The rationale behind this approach is that it is not possible to deploy a single component without also installing the rest of the system necessary for its operation. On the other hand, R&D shocks can be targeted at either an entire technology or towards individual components that cannot be deployed independently (for example, an on-board reformer for a fuel cell vehicle). Consequently, D&D shocks applied to one technology can directly stimulate the learning process for common components used by other technologies, whereas R&D shocks tend to be specific to a single technology, and spillover benefits mainly occur when the R&D shock leads indirectly to additional technology installations.

In this analysis we report the result of orthogonal R&D shocks and D&D shocks. The size of the R&D shock for each technology is set at 20 percent of cumulative R&D expenditure as at 2000 for that technology. By standardizing the size of the R&D shocks we ensure that we do not apply absurdly large shocks to infant technologies (which are likely to saturate any response and reduce the impact per unit of expenditure), or unrealistically small shocks to mature technologies compared to the current levels of R&D investment. Through this approach, it is hoped that the results will better provide policy makers with a clearer indication of the potential impact on sustainability indicators of a given investment in R&D.

However, for D&D shocks we take a slightly different approach, and apply a one-off shock of 10 billion euros (€1999) to each energy technology of interest. Using a similar approach to that applied in the EC-sponsored MINIMA-SUD project (Barreto and Turton 2005), a standard D&D shock size has been chosen in order to be able to compare the effects of D&D shocks for different technologies on a common basis. Unlike R&D shocks, it is not necessary to standardise relative to previous investment because this is implicitly accounted for by the higher investment costs of less mature technologies. That is, *ceteris paribus*, €10 billion buys less capacity of an immature technology than a mature technology, so the new capacity installed as a result of the shock is already somewhat standardised.

It should be noted that the D&D shocks applied for this exercise account for the total capital cost of deploying new capacity. This is important because, in reality, a policy-maker (i.e., a government) may not need to pay this entire cost, but rather the difference in cost between the 'shocked' technology and the technology that would have been deployed in the absence of policy intervention. A proper accounting requires the assumption that the policy-maker subsidises the full net present value difference between the shock and baseline technology options, so as to also account for differences in operating, maintenance and fuel costs. Accordingly, although for simplicity most of the analysis focuses on the impacts of standardized D&D shocks, the accompanying to the ERIS report Excel file allows the user to calculate impacts adjusted for appropriate baseline technology costs.

Like the R&D shocks, the D&D shocks shed some light into which technology would provide a larger “return-on-investment” in terms of the impact on sustainability indicators if a corresponding D&D program of the above-mentioned size were implemented. In doing so, the use of a standard size for the D&D shock greatly facilitates the comparison across technologies. As mentioned earlier, this analysis seeks to calculate “impacts” defined as the ratio Δ-Indicator/Instrument Cost, where “Δ-indicator” is computed as the change relative to the baseline scenario. The costs of either R&D or D&D programs are measured at “face value”, i.e., as the respective R&D and D&D expenditures that constitute a shock.

Orthogonal shocks have been performed for electricity generation, fuel production, passenger vehicle, carbon capture technologies and system components. The list of technologies, their abbreviations and the types of shocks applied are presented in Table 2-1. In a following section we also examine with ERIS the effects of non-orthogonal shocks combining R&D and D&D shocks.

As shown in Table 2-1, although R&D shocks are applied to all technologies assumed to benefit from learning-by-searching, not all technologies that may benefit from learning-by-doing are subjected to a D&D shock. This is because in many cases it is not considered realistic that additional public support would be provided to technologies considered to be mature or competitive, such as conventional coal, nuclear, large hydro and conventional oil generation.

In all cases, it is important to remember that the ultimate impact of any shock depends on many factors, limited not only to technology learning and clustering but also constraints on market penetration, resource potentials, costs and availability, and the climate change policy assumed also for these shock exercises.

Table 2-1: Description and abbreviations of technologies in the electricity generation, fuel production, passenger-car and carbon capture sectors for which R&D and D&D shocks were performed.

Sector	Technology Description	Abbreviation	Type of shock D&D	Type of shock R&D
Electricity generation technologies	Coal Conventional Thermal	HCC		x
	Integrated Coal Gasification Combined Cycle	HCA	x	x
	Oil Conventional Thermal	OLC		x
	Gas Turbine Combined Cycle	GCC	x	x
	Gas Conventional Thermal	GSC		x
	Gas Turbine Open Cycle	GTR	x	x
	Gas Fuel Cell (generic stationary)	GFC	x	a
	Nuclear (2nd and 3d gen.)	NUC		x
	New Nuclear (4th gen.)	NNU	x	x
	Biomass	BIP	x	x
	Large Hydro	HYD		x
	Solar Thermal	STH	x	x
	Photovoltaic	SPV	x	x
	Wind Turbines Onshore	WND	x	x
	Hydrogen Fuel Cell (generic stationary)	HEF	x	a
Hydrogen production technologies	Hydrogen from Gas Steam Reforming	GASH2NE	x	x
	Hydrogen from Coal Partial Oxidation	COALH2NE	x	x
	Hydrogen from Biomass Pyrolysis	BIOH2NE	x	x
Passenger transport technologies	Gasoline-powered hybrid-ICE-electric car	ICH	x	b
	Gas-powered hybrid-ICE-electric car	IGH	x	b
	Alcohol-powered hybrid-ICE-electric car	IAH	x	b
	Hydrogen-powered hybrid-ICE-electric car	IHH	x	b
	Gasoline-powered fuel-cell car	PFC	x	a
	Alcohol-powered fuel-cell car	AFC	x	a
	Hydrogen-powered fuel-cell car	HFC	x	a
Carbon capture technologies	Pre-Combustion CO_2 capture (Integrated Gasification Combined Cycle)	HCACS	x	x
	Post-Combustion CO_2 capture (Conventional Coal)	HCCCS	x	x
	Post-Combustion CO_2 capture (Gas Turbine Combined Cycle)	GCCCS	x	x
	Pre-Combustion CO_2 capture (Hydrogen production)	H2CAS	x	x
Technology components	Generic fuel cell component	FCMS		x
	Hybrid-electric vehicle component	HYBV		x
	Pure electric vehicle component	ELVT		x
	Hybrid battery system component	HYBB		x

a. R&D shock benefits technology through impact on "Generic fuel cell component."
b. R&D shock benefits technology through impact "Hybrid-electric vehicle component", "Pure electric vehicle component" and 'Hybrid battery system component."

2.1. An illustrative R&D policy shock

Before we present the results for all of the technologies in Table 2-1 that are assumed to benefit from learning-by-searching, it is helpful to present in detail first a single illustrative R&D shock.[24] This example illustrates some of the possible ways in which R&D expenditure on a single technology can not only affect the competitiveness of that technology and through it the development of the energy system, but can also result in indirect spillovers that benefit other unrelated technologies through interactions that a comprehensive energy-system model like ERIS is able to examine. Examining in detail

---

[24] Note, for comparison, the impact of an illustrative D&D shock is reported in Barreto and Turton (2005) – a report prepared for the EC-sponsored MINIMA-SUD project.

one example also provides the reader with an appreciation of the possible difficulties that may arise when comparing a large number of R&D shocks.

The example presented here is an R&D expenditure shock to the fuel cell technology. Specifically, a shock of 20 percent of cumulative R&D expenditure was applied in the base year (2000) to the generic fuel cell technology. This is estimated to be roughly equivalent to $7.5 billion in R&D expenditure (from a combination of private-sector and government), or slightly more than 1.1 percent of cumulative global energy R&D for energy conversion and transport as at 2000 (refer to spreadsheet accompanying Kouvaritakis and Panos 2005).

As described in Kouvaritakis and Panos (2005), one 2FL equation is used to represent the capital cost of all fuel cell technologies, comprising both stationary and mobile technologies. As a consequence, an R&D shock on the generic fuel cell technology is expected to benefit a number of diverse applications of fuel cells. Furthermore, because many of these different fuel cell applications compete in entirely separate energy and technology markets, the impact on the development of the energy system has the potential to be wide-reaching.[25] In addition, the effect of an R&D shock is likely to be reinforced by the impact of learning-by-doing, and a small competitive advantage afforded by an R&D shock may translate into the realization of a wholly different technological development path.

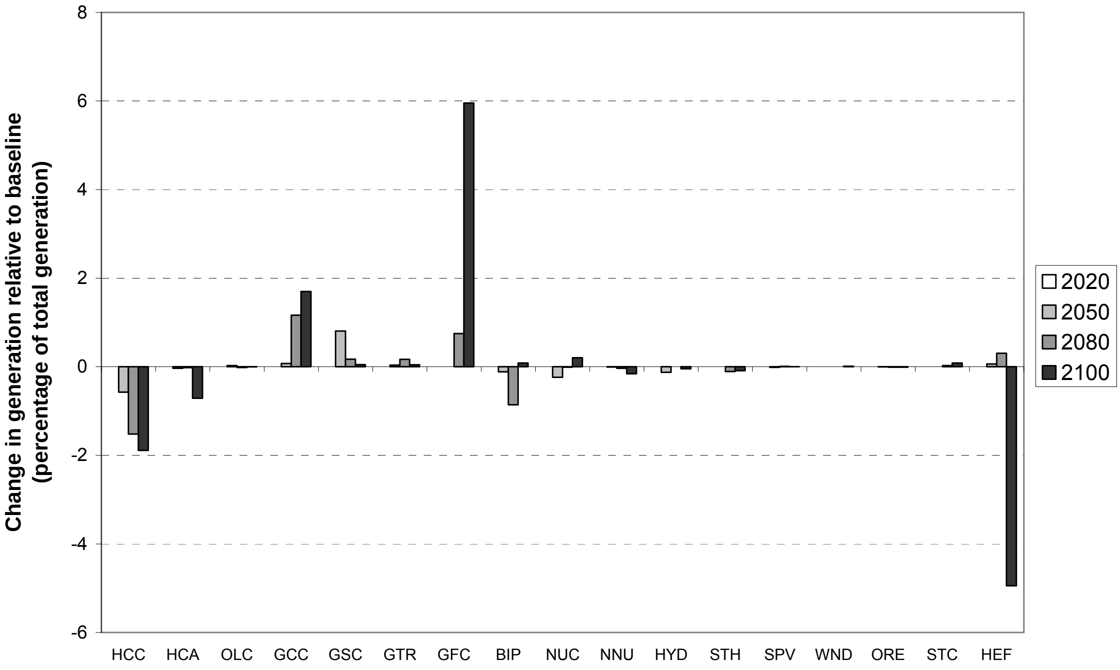
The impact on the future energy system of an R&D shock on the generic fuel cell technology is described below. Figure 2-1 compares the global electricity generation mix under this R&D shock with the baseline scenario across a number of timepoints in the 21st century.

Figure 2-1 appears to show that the overall impact on the electricity sector, both in scope and scale, is very similar to that presented for the «R&D Doubling» scenario in Figure 2-1: . The main elements comprise a shift from hydrogen to gas fuel cells, increased generation from other gas-fired technologies, and lower generation from coal. Importantly, as in the «R&D Doubling» scenario, total electricity generation from stationary fuel cells is largely unchanged from the baseline scenario – that is, under the assumptions used here fuel cells are already competitive in this sector without the R&D shock. However, in the transport sector the shock has a major effect on FC competitiveness, although again the result is similar to the «R&D Doubling» scenario (Section D-II.2), as shown in Figure 2-2.

---

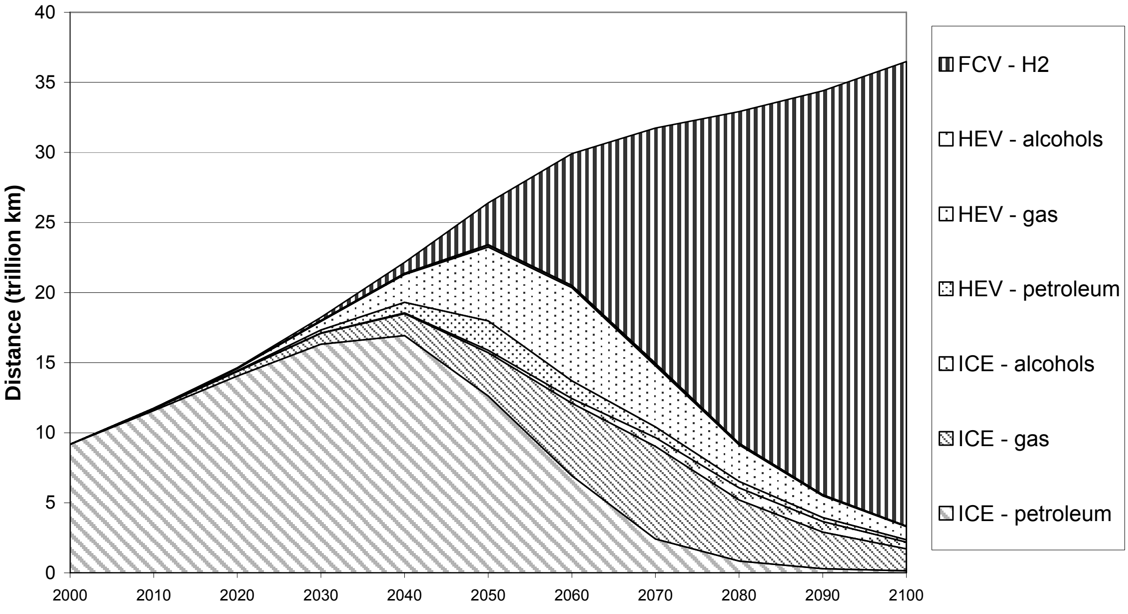
[25] As we saw in Section DII 2 the impact on fuels cells of the optimistic R&D scenario resulted in significant changes to the energy system.

Figure 2-1: Change in global electricity generation under fuel cell R&D shock, relative to baseline (2020, 2050, 2080, 2100)



Note: Technology abbreviations are as follows: HCC: conventional coal, HCA: advanced coal (IGCC), OLC: oil conventional, GCC: gas combined-cycle, GSC: gas steam cycle, GTR: gas turbine, GFC: gas fuel cell, BIP: biomass gasification, NUC: nuclear conventional, NNU: new nuclear, HYD: hydro, STH: solar thermal, STC: solar thermal cogeneration, SPV: solar photovoltaics, WND: wind turbine, ORE: other renewables, HEF: hydrogen fuel cell.

Figure 2-2: Global technology and fuel choice for passenger car travel with fuel cell R&D shock



Accordingly, under the modelling and policy assessment framework assumptions used here, the R&D shock applied solely to fuel cells (approximately €7.5bn) results in much the same transformation of the electricity and transport sectors (and the energy system as a whole, for that matter) as the much larger-scale additional R&D investment (>€400bn) in the «R&D Doubling» scenario. The effect on key indicators of sustainability is also much the same, as shown in Table 2-2, although the impacts are approximately 50-fold higher because the R&D expenditure is much more efficiently targetted.

Table 2-2: Calculation of impact on sustainability indicators of fuel cell R&D shock

Indicator	**Baseline**	**Shock**	**Δ**	**Percentage**	**Impact**	
						Units
CO_2 conc. (2100) (ppm)	702	695	-7.3	-1.04	-0.98	ppm/€bn
CH_4 conc. (2100) (ppm)	2539	2532	-6.9	-0.27	-0.92	ppb/€bn
Temperature change (K) (2100)	3.24	3.27	0.032	0.99	4.29E-03	K/€bn
Temperature change (K) (2100) (constant sulfate)	2.73	2.71	-0.020	-0.75	-2.72E-03	K/€bn
Sea-level rise (cm) (2100)	40.8	41.0	0.21	0.51	0.028	cm/€bn
Oil resource-to-production ratio (years) (2060)	32.6	33.7	1.2	3.62	0.16	years/€bn
Gas resource-to-production ratio (years) (2060)	45.2	44.4	-0.8	-1.80	-0.11	years/€bn

Note: rounding errors mean that reported Δs may differ from the apparent difference between the 'Baseline' and 'Shock' cases. The raw results are reported in Appendix Tables A3 and A4.

These results imply that well-targeted investments aimed at key technologies have the potential to substantially change the development of the energy system, although the impact on indicators of sustainability over this timeframe is generally small. However, when combined with complementary initiatives, additional R&D investment may have the potential to contribute to the realization of sustainability objectives. We now examine whether other R&D shocks are also able to improve sustainability indicators, with the following section summarising the results of the standardised R&D shocks for all of the technologies indicated in Table 2-1.

2.2. Summary of orthogonal R&D shocks

This section explores in brief the impact of a series of independent R&D investments in the base year (2000), on the main sustainable-development indicators. Detailed results from this orthogonal shock exercise are presented in the Appendix (Tables A3 and A4). Importantly, the results reported here comprise entirely "impacts", rather than indicator levels. That is, for each sustainable development indicator we present only the change in that indicator (relative to the ERIS baseline scenario) per billion euros of additional R&D investment. The detailed example in Section 2.1 for the fuel cell component illustrated how these impacts are calculated.

As we saw also in this example, although the magnitude of the changes that an R&D shock induces on the energy system may be large using this methodology, the impact on sustainability indicators can be small. This is confirmed for most shocks in Figure 2-3, which presents the impact on atmospheric CO_2 concentration at the end of the century under each shock. The biggest impacts appear to occur when an R&D shock is applied to either of two carbon capture technologies (GCCCS and HCCCS), and the biomass-to-hydrogen production technology ($BIOH_2NE$).[26] However, these also happen to be three of the technologies that have historically received the least R&D support, and since the

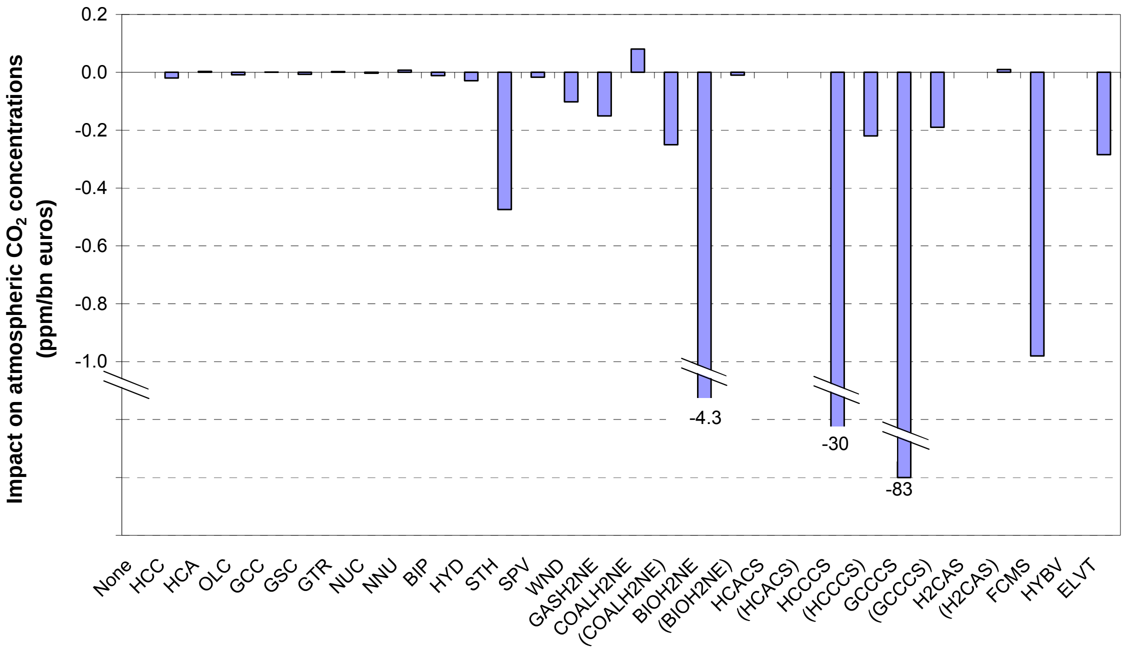
---

[26] For description of abbreviations, see Table 2-1 on page 400.

size of the shock is standardised to cumulative historical R&D investment, these technologies receive relatively small shocks (less than €50 million). This tends to exaggerate the size of any impact, even if insignificant. Accordingly, we also present the impacts from a €1 billion shock to each of these technologies (in addition, we apply the same shock also to two other carbon capture technologies (HCACS, H_2CAS) and coal-to-H_2 production ($COALH_2NE$), which have also historically received very little R&D support). The impacts under the €1 billion shock are much lower, in both relative *and in most cases absolute* terms, which indicates that these shocks do not have a particularly significant impact on atmospheric CO_2 concentrations, or any impact saturates at very low levels of additional R&D support.

Taking this into account, the biggest impact occurs with the R&D shock applied to the generic fuel cell technology. The impact of the R&D shock on solar thermal electricity generation may also be significant, but the absolute change in concentration was very small under this shock, however the size of the shock is just above €1 billion.

Figure 2-3: Impact of R&D shocks on atmospheric CO_2 concentrations in the year 2100, relative to baseline



Note: For abbreviations of the technologies see Table 2-1. Impacts are reported in a way that is consistent with the change in the underlying indicator, so that a negative impact means the indicator decreased, and a positive impact means the indicator increased.

This result highlights the potential importance of fuel cells in a scenario based on the assumptions applied here. Conversely, for many other technologies it appears that these assumptions, such as the climate policy, resource endowments, and penetration and diffusion constraints for new technologies, are more significant than the impact of the R&D shock. In some ways this is a consequence of using a perfect-foresight model, which has a tendency to either install a technology to the maximum allowable extent or not to install it at all. Generally speaking then, an R&D shock will only have an impact when it results in an uncompetitive technology becoming competitive. Of course, both the model and reality are more complex this, and regional characteristics, the existence of niche markets and other factors mean that this "all-or-nothing" behavior will not necessarily occur.

However, it is important to stress the significance of the climate policy assumed in this analysis when interpreting these results. Under the baseline scenario with no R&D

shocks) all GHG abatement opportunities that cost less than the rate of the GHG tax that represents the climate policy are exploited, and this determines total emissions (and hence climate impacts). Accordingly, an R&D shock will only produce additional abatement if it reduces the cost of some of the abatement opportunities from above the GHG tax rate to below the GHG tax rate. This means that if the R&D shock makes abatement opportunities that are already competitive slightly cheaper, it will not reduce emissions (although it will reduce total system costs). On the other hand, if the R&D shock makes uncompetitive abatement slightly cheaper, but not cheaper than the GHG tax rate, it will have no significant impact on technology choice. This is illustrated in Figure 2-4. Accordingly, the stringency of the climate mitigation policy can have a significant bearing on the potential impact of an R&D shock. A different climate policy would be expected to change the relative impact of R&D shocks applied to different technologies, and may identify alternative technologies as possible targets for R&D support. This was seen, for example, for a combination of D&D shocks and GHG taxes in the EC-sponsored MINIMA-SUD project (Barreto and Turton 2005).

We now turn to some of the other sustainability indicators, and in Figure 2-5 we present the impact of the R&D shock on temperature in 2100. In this figure, we report only the larger shocks for those technologies for which the standardised shocks are very small (GCCCS, HCCCS, HCACS, H_2CAS and BIOH$_2$NE). The full results for these technologies are available in the Appendix (Tables A3 and A4) and the to the ERIS report spreadsheet, but once again, the absolute change in the indicator is effectively unchanged under the larger R&D shock indicating that these shocks do not have a significant impact or saturate at very low levels.[27]

Figure 2-5 presents temperature change including and excluding the impact of sulfate aerosols. Looking first at the series with constant aerosol emissions, we see results that are entirely consistent with those for concentration in Figure 2-3 – with the largest impact on temperature occurring under the R&D shock to the fuel cell technology. As with concentrations, the effect with the solar thermal (STH) technology also appears to be significant, although the absolute change is very small (and this is the case for all the other technologies). When the impact on emissions of sulfate aerosols is also included, the picture is substantially different. The fuel cell shock goes from reducing temperature to increasing temperature because it displaces coal use (primarily coal-fired electricity generation as shown in Section 2.1), and presumably this also happens with the solar thermal shock.

---

[27] Except for the shock applied to BIOH$_2$NE, where the direction of the change in the indicator changes as the size is increased. Again, this implies that the impact is insignificant.

Figure 2-4: Illustration of impact of shock on level of GHG abatement

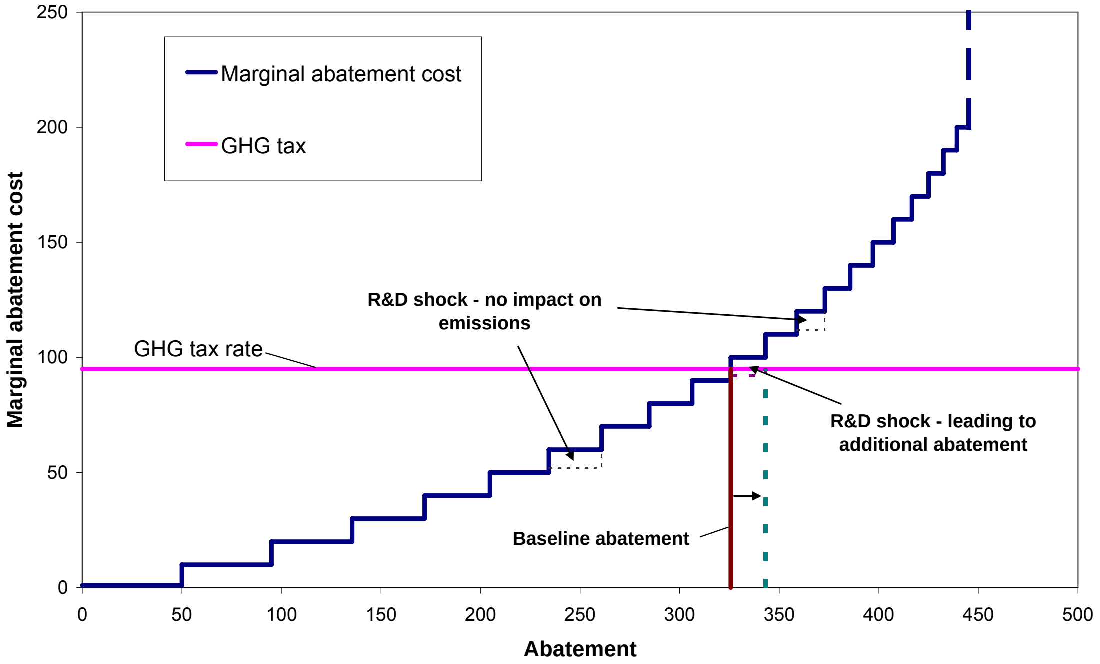
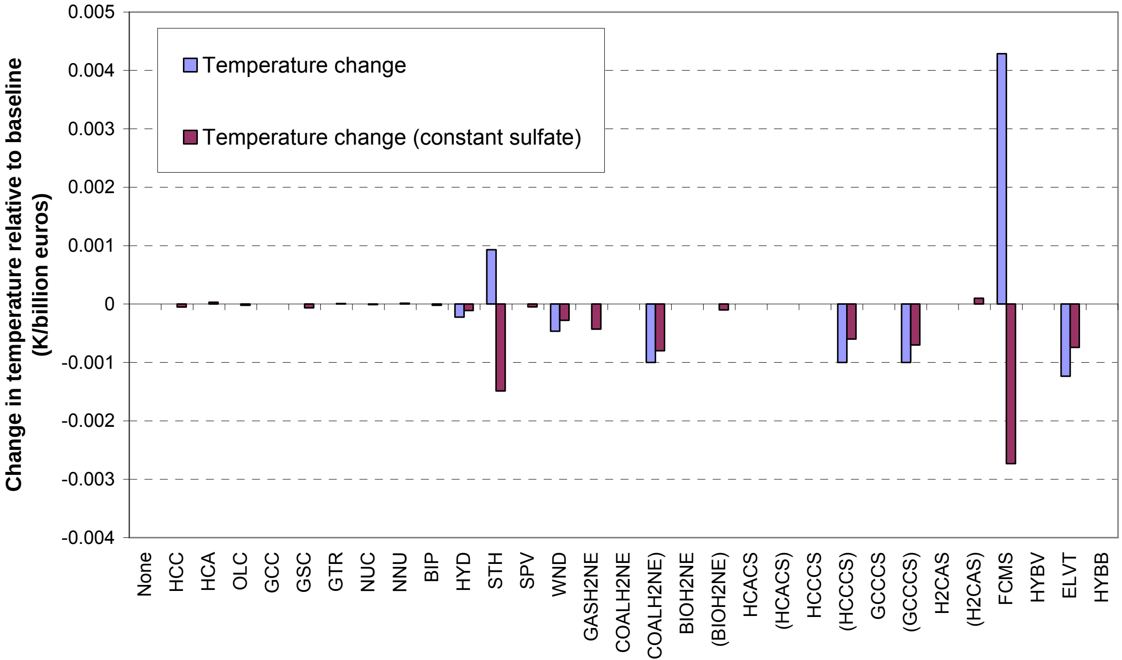


Figure 2-5 Impact of R&D shocks on global average temperature in the year 2100, realtive to baseline

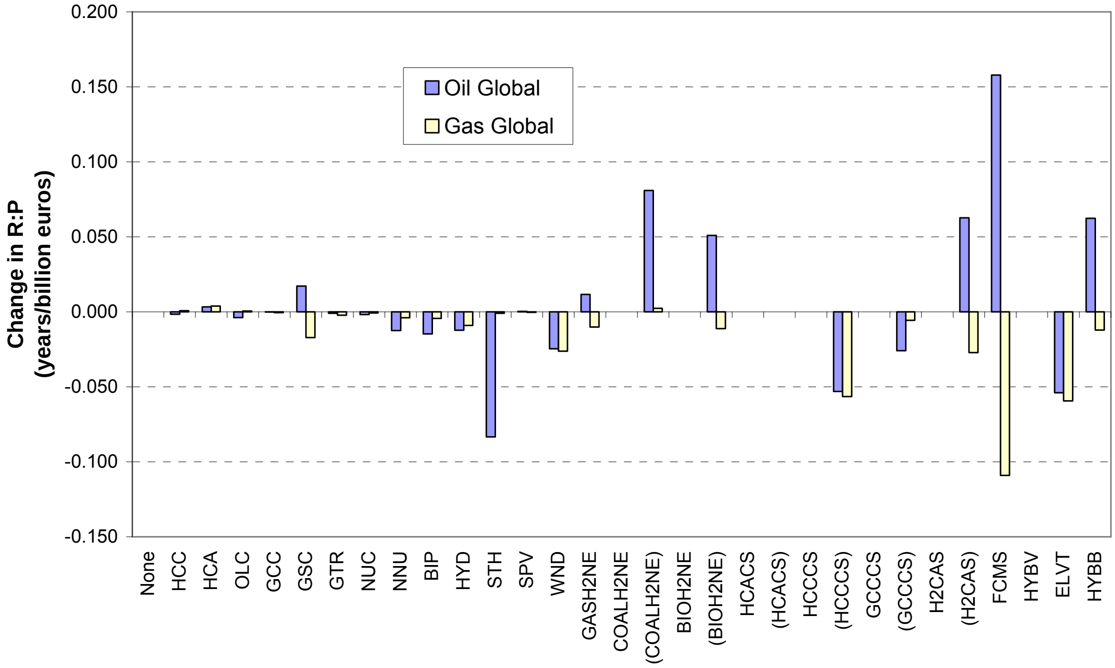


Note: For abbreviations of the technologies see Table 2-1. Impacts are reported in a way that is consistent with the change in the underlying indicator, so that a negative impact means the indicator decreased, and a positive impact means the indicator increased.

This leads to the somewhat perverse conclusion that one possible way of effectively mitigating climate change impacts is to support technologies that produce emissions of sulfur oxides (but minimal GHG emissions), whereas supporting the technology that is the most effective at reducing carbon emissions results in a higher global average temperature. However, this result occurs partly because adoption of fuel cells is still somewhat constrained, which implies that other factors limiting the deployment of fuel cell technologies also need to be addressed, in conjunction with any R&D policy support. These include the need to both mobilise new resources and technologies for hydrogen production, and finance the cost of establishing the necessary infrastructure for hydrogen distribution, possibly through public-private partnerhships. Demand-pull measures may also be need to accelerate market acceptance of new technologies, including procurement programs, tax credits and other measures.

The last sustainable-development indicator that we will present in this section is the global resources-to-production ratio for oil and gas in the year 2060. The impact on this indicator for each R&D shock is presented in Figure 2-6, where the largest positive impact on oil security occurs with the shock applied to the generic fuel cell technology. In addition, shocks to biomass- and coal-to-hydrogen (BIOH$_2$NE COALH$_2$NE), hybrid vehicle battery systems (HYBB) and carbon capture from advanced coal (HCACS) also apparently have a positive impact. This indicates that support for hydrogen technologies can potentially result in early deployment of these technologies, providing a flexible and convenient alternative to gas and oil. In addition, supporting technologies that improve the efficiency of oil consumption, such as the hybrid battery system can also extend oil availability.

Figure 2-6: Impact of R&D shocks on global oil and gas resource-to-production ratios in 2060, relative to baseline



Note: For abbreviations of the technologies see Table 2-1 on page 400. Impacts are reported in a way that is consistent with the change in the underlying indicator, so that a negative impact means the indicator decreased, and a positive impact means the indicator increased.

Interestingly, the R&D shock to solar thermal generation worsens oil security, as do a number of other shocks targeted at technologies that may be able to contribute to a substitution of other energy sources for oil. This also occurs with gas security for many of the shocks. The explanation of why many of the shocks result in lower security for gas (and in some cases oil) is that the climate change policy appears to gear the energy system towards displacing coal. Consequently, if a shock can create additional ways of replacing coal with other fuels, including gas (and in some cases oil), then these are likely to be exploited resulting in lower R:P ratios. The fact that gas and oil are used, even though renewable and nuclear energy can theoretically displace coal, appears to be because most of the cost-effective nuclear and renewable options are already exploited under the baseline scenario; which is also why shocks to nuclear and renewable technologies have little impact. One exception appears to be solar thermal generation, but the R&D shock to this technology also appears to create additional opportunities to use oil, most likely to displace coal.

This concludes the more detailed discussion of the standardised R&D shocks. Those sustainability indicators not discussed in detail, including changes in atmospheric methane concentration, sea-level rise, and security of energy supply in Europe, are presented quantitatively in the Appendix and the accompanying to the ERIS report spreadsheet.

Again, it is very important to re-emphasise that the impact of the R&D shocks depends significantly on the baseline scenario. Specifically, under the scenario considered here the assumed climate change mitigation policy (a GHG tax) means that a number of new low-emissions technologies are already competitive. Additional greenhouse gas abatement only occurs when an R&D shock brings the abatement cost associated with the deployment of a previously uncompetitive technology to below the level of the GHG tax. Under the climate change policy assumed for this exercise, the R&D shock applied to fuel cells was the most (and possibly only) effective shock in terms of the indicators of climate change. Furthermore, it also had the largest impact on security of energy supply, being effective at extending the oil R:P ratio. However, although this shock results in a significant transformation of the energy system (as seen in Section 2.1), the impact on the climate change indicators was only small because of the effect of other factors. Clearly, any overall strategy to achieve sustainability goals through support for energy technology R&D, should include additional policy elements that complement and fully exploit the impact of the R&D policy. One possible set of complementary measures comprise support for demonstration and deployment (D&D) programs that attempt to accelerate technology adoption by focusing on the demand side. The next section explores the possible impact of such D&D programs, by applying orthogonal D&D shocks to the technologies indicated in Table 2-1.

2.3. Summary of orthogonal D&D shocks

In this section we present the impact of a series of demonstration and deployment (D&D) shocks on the same suite of indicators discussed in the preceding section. These deployment shocks are applied in much the same way as the R&D shocks – that is, independently (orthogonally) and in the base year (2000); the magnitude of each D&D shock is €10 billion. In this section we present only "impacts" calculated based on the full cost of the D&D shock, although we also report impacts calculated on the basis of an adjusted shock cost that accounts for the cost likely to be faced by policy-makers (as discussed at the start this section) in the Appendix in Table A4, and in the accompanying to the ERIS report spreadsheet. Further, although the focus here is on "impacts", in many cases it leads naturally to a discussion of indicator levels (which are also reported in the Appendix in Table A3, and in the accompanying to the ERIS report spreadsheet).

Unlike for the R&D shock exercise, we do not present a detailed example of the impact of a D&D shock. Instead, readers are referred to the IIASA/ECS report for the EC-sponsored MINIMA-SUD project (Barreto and Turton 2005), which presents in detail an illustrative example of the impact of a single D&D shock.

As we emphasised in the discussion of the R&D shocks, the reader should bear in mind that the impacts of demonstration and deployment (D&D) shocks depend on the baseline scenario. The assumed baseline technology development and climate policy may have a large bearing on the potential impact of any D&D shock.

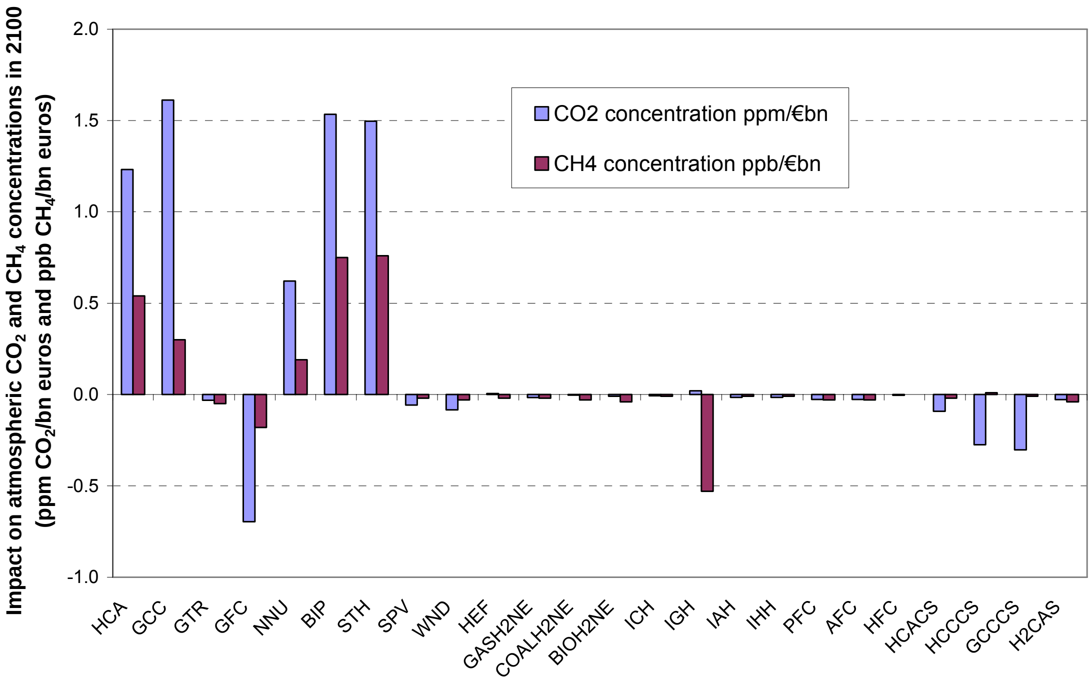
2.3.1. Atmospheric CO_2 and CH_4 concentrations

Unlike the R&D shocks, D&D shocks affect technology learning by forcing deployment of the shocked technology. This deployment not only results in additional experience with the technology, but creates new energy-system opportunities and therefore results in different impacts to the R&D shocks, which do not necessarily lead to technology deployment.

This is illustrated for the impact on atmospheric concentrations of CO_2 and CH_4 under the D&D shocks as shown in Figure 2-7. Compared to the R&D shock impacts in Figure 2-3, the impacts in Figure 2-7 affect different technologies and appear to produce worse sustainability outcomes for atmospheric GHG concentrations. In some cases this is expected, such as for the impact on CO_2 concentrations of the shock applied to advanced IGCC generation, because it accelerates the deployment and improves the competitiveness of a relatively more emissions-intensive technology. However, somewhat surprisingly, a demonstration and deployment shock applied to either gas combined cycle generation (GCC), biomass generation (BIP) or solar thermal generation also results in higher atmospheric CO_2 concentrations.

Closer examination reveals that in all three cases, the shock increases the competitiveness of the shocked technology leading to installation of additional generation capacity which helps to defer the adoption of, and ultimately lock out, hydrogen fuel cell electricity generation. However, over the longer term none of the shocked technologies is able to make a sufficiently large contribution to electricity generation because of constraints on resource availability (gas and biomass), and intermittency in the case of solar thermal generation. As a consequence, heavy reliance on conventional coal-fired generation continues longer than under the baseline scenario, resulting in higher emissions and atmospheric concentrations of CO_2.

Figure 2-7: Impact of D&D shocks on atmospheric CO_2 and CH_4 concentrations in the year 2100, relative to baseline



Note: For abbreviations of the technologies see Table 2-1 on page 400. Impacts are reported in a way that is consistent with the change in the underlying indicator, so that a negative impact means the indicator decreased, and a positive impact means the indicator increased.

Similarly, a D&D shock applied to advanced nuclear generation also locks out the use of fuel cells, but unlike the three technologies discussed above, nuclear generation is assumed to be able to make a large-scale contribution to total generation. This means that coal-fired generation is displaced by nuclear earlier and on a larger scale than with the renewables or GCC, resulting in lower GHG emissions (although they are still higher than under the baseline because the additional nuclear generation is unable to fully offset the decline in generation from fuel cells). It should briefly be mentioned that this result for advanced nuclear generation is different to that presented in Barreto and Turton (2005) for the EC-sponsored MINIMA-SUD project mainly because of different technology assumptions regarding fuel cells.[28]

So far we have discussed those D&D shocks that exacerbated climate change, but there are a number, however, that result in abatement and lower atmospheric CO_2 concentrations. The largest reduction occurs with the shock applied to the gas fuel cell technology. This is not unexpected considering the importance of fuel cell generation over the century under the baseline scenario. This shock accelerates the deployment of gas fuel cells, which reduces reliance on other gas and coal-fired generation. However, the additional and early experience with fuel cells is not sufficient under the assumptions applied here to result in widespread adoption of fuel cells in transportation.

An interesting result of the shock exercise is that an identical shock applied to stationary hydrogen fuel cell generation has almost no impact on the climate change indicators of interest. This result is not surprising however, if one considers that the deployment of hydrogen fuel cell generation cannot have any significant impact on the energy system because of insufficient hydrogen production and limited distribution infrastructure – this deployment shock results in construction of a “white elephant”. This highlights the importance of adopting a co-ordinated strategy when supporting new technologies, that accounts for upstream and downstream requirements for successful deployment – in this case, the D&D policy should be complemented by support for accelerated investment in hydrogen production and distribution infrastructure, and possibly carbon capture technology.

Other shocks that result in a noticeable reduction in emissions are those applied to carbon capture technologies for post-combustion capture from conventional coal and gas generation. The accelerated deployment and experience with these technologies reduces emissions earlier in the century, but because the associated electricity generation technologies play a declining role later in the century, these shocks have only a limited impact.

Deployment shocks applied to capture technologies that currently have no market – that is, carbon capture from advanced IGCC generation and from hydrogen production – have no impact because only very limited experience is gained. Similarly, shocks applied to hydrogen production technologies have essentially no impact because of limited hydrogen distribution infrastructure or hydrogen demand initially. As briefly mentioned already, this highlights the need to co-ordinate technology support policies so that they target all of the key elements in the energy chain, particularly where the deployment of each of these elements is confronted by significant barriers. Hydrogen-based technologies are perhaps the best examples of this because they are highly interdependent and all elements need to be in place before any of the potential benefits of a hydrogen-based energy system can be realised. The need for large-scale co-ordinated investment in such systems implies that there may be a role for government intervention, particularly in co-ordinating infrastructure planning and accepting some of the risk associated with interdependent capital-intensive investment.[29]

---

[28] Specifically, the technology learning parameters in MINIMA-SUD reflected lower optimism regarding the potential effect of learning-by-doing on the cost of stationary fuel cell generation capacity, which meant this technology was less attractive, and consequently that a D&D shock to advanced nuclear did not displace fuel cells.

[29] There may well also be an important government role in regulating what are likely to be monopoly hydrogen distribution assets.

The relative impact of the D&D shocks on atmospheric concentrations of methane at the end of the 21st century closely resembles the impact on CO_2 concentrations. This is somewhat surprising because shocks were applied to very different technologies (e.g. coal, gas, renewables, nuclear, fuel cells), which are expected to have different impacts on natural gas consumption. Natural gas production is the only source of methane emissions that differs under the shocks, since the D&D shocks are assumed not to change methane emissions from other activities such as agriculture.

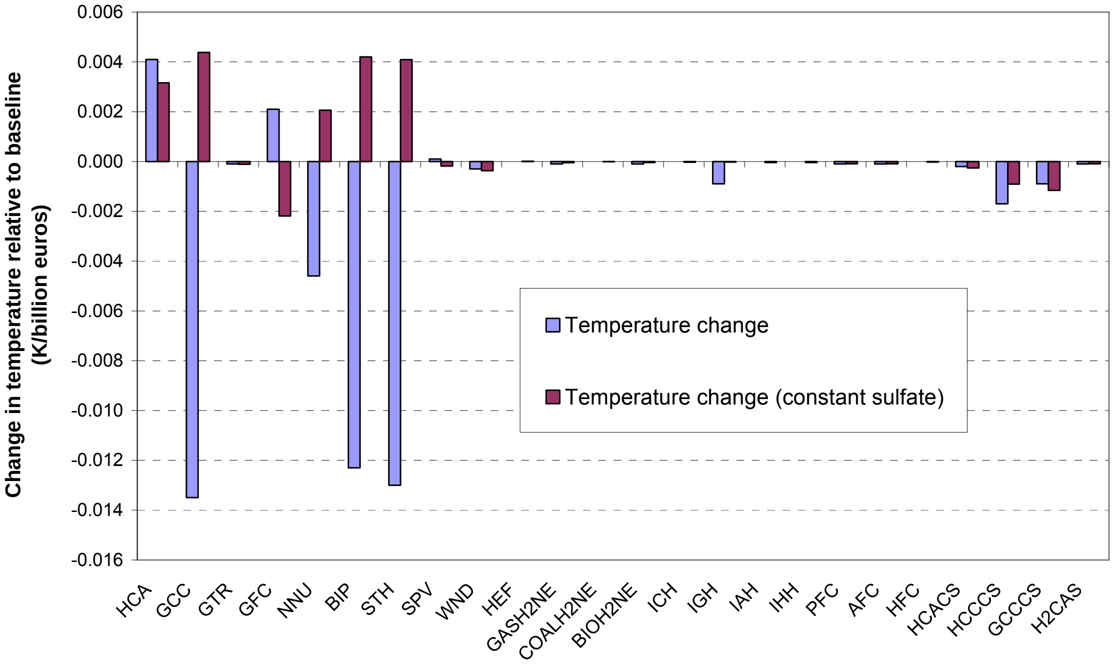
However, in addition to displacing hydrogen fuel cell generation, many of these shocks also displace natural gas generation through the first half of the century and hence reduce methane emissions (although in all cases the impact is very small compared to the total methane concentration). This is even the case for the shocks applied to gas combined cycle (for a short period) and fuel cell generation, which displace other less-efficient forms of gas consumption. However, it appears that under many of these shocks, most of the gas that was saved earlier in the century is exploited towards the end. The tendency of the shocks to shift gas consumption to later in the century, combined with the short atmospheric residence time of methane, means that the many shocks increase methane concentrations in 2100. However, for the shock to gas fuel cells and gas hybrids (IGH) this does not occur. The early deployment of gas fuel cells under this D&D shock continues to keep gas consumption slightly lower throughout much of the century, and even though there is an increase towards the end, it is relatively small. Conversely, the gas hybrid D&D shock works in the opposite way to the other shocks by increasing gas consumption earlier in the century, meaning that less gas is available towards 2100.

Temperature

The impact of the standardised D&D shocks on temperature change relative to the baseline scenario is presented in Figure 2-8. Looking first at the results with constant sulfate aerosols, the greatest temperature increase occurs with the gas combined-cycle D&D shock, followed by the biomass and solar thermal shocks. Because of their impact on locking out one of the least emissions-intensive technologies, these three shocks produce more climate warming than the shock applied directly to IGCC generation (HCA). Accordingly, these results mirror those for atmospheric CO_2 concentrations. Similarly, the D&D shocks that reduce concentrations – comprising the shocks to gas fuel cells and two carbon capture technologies – result in equivalent mitigation of temperature change.

The impact estimates in Figure 2-8 that incorporate the effect of changes in aerosol emissions are somewhat more complicated. Perversely, those D&D shocks that lock out hydrogen fuel cells thereby resulting in additional generation from conventional coal, actually result in smaller temperature increases because of higher SO_x emissions from coal generators. On the other hand, the shock applied to advanced coal generation results in both higher coal use and lower SO_x emissions because IGCC generators are assumed to include desulfurisation units, contributing to a large increase in temperature. However, the D&D shock applied to the natural gas fuel cells also leads to this outcome, again because it displaces coal-fired generation and therefore reduces both CO_2 and SO_4^{2-} emissions.

<u>Figure 2-8 Impact of D&D shocks on global average temperature in the year 2100, realtive to baseline</u>



Note: For abbreviations of the technologies see Table 2-1 on page 400. Impacts are reported in a way that is consistent with the change in the underlying indicator, so that a negative impact means the indicator decreased, and a positive impact means the indicator increased.

2.3.2. Security of supply

The discussion so far of the impact of the D&D shocks on other sustainability indicators has touched on some issues related to energy security of supply. We now focus on the impact on gas and oil resources-to-production ratios in more detail, to explore some of the possible impacts on security of D&D programs.

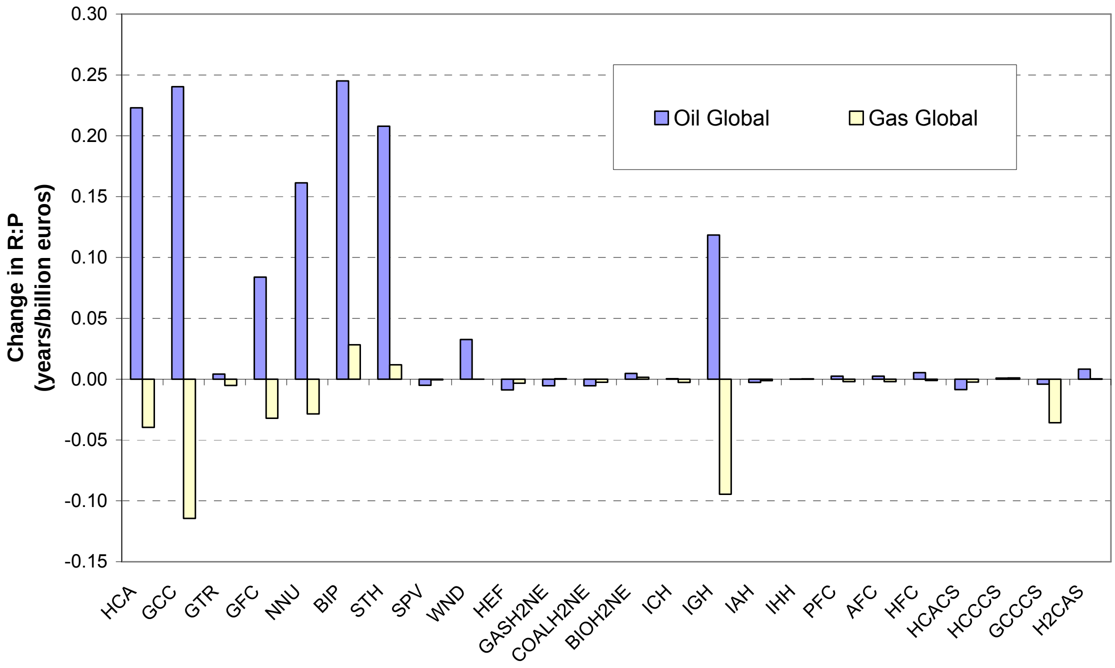
Figure 2-9 shows that almost all of the shocks that were observed to have a significant impact on the other indicators of sustainability, also have an impact on security of energy supply. In general, these D&D shocks tend to increase global oil availability and decrease or leave roughly unchanged, gas availability in 2060. The impact on oil can be explained by the fact that these shocks facilitate additional energy production from technologies that do not use oil, consequently leading to lower oil consumption and extending the life of oil resources. The biggest impacts on long-term oil security occur with D&D shocks applied to advanced coal IGCC, natural gas combined-cycle, advanced nuclear, biomass and solar thermal generation. Smaller positive impacts arise with demonstration and deployment of gas fuel cells and gas hydrid vehicles.

The impact of these shocks on natural gas resources-to-production ratios is consistent with the earlier discussion of these shocks, particularly in relation to methane emissions. In Section 2.3.1 above, we noted that many of these shocks displace gas consumption earlier in the century, resulting in higher gas consumption in the second half of the century. However, for shocks to gas combined cycle generation and gas hybrids, gas consumption is encouraged from earlier in the century, which results in the greatest impact on the R:P for gas (see Figure 2-9). The shocks to IGCC, gas fuel cells, advanced nuclear, biomass and solar thermal generation result in smaller impacts, and diverge depending on how advanced the shift back to gas is by 2060 in these scenarios. The actual pattern of gas consumption in each of these scenarios is quite complicated, and it is beyond the scope of this report to describe them in detail. However, a general note is that gas is a very attractive fuel under the assumptions applied here – it has a low carbon content and is flexible and convenient – so any D&D shock that provides a way to use more gas in place of less attractive fuels can be expected to be fully exploited over time.

It should also be noted from Figure 2-9 that there appears to be a trade-off between the two indicators of global security of energy supply. That is, shocks leading to a larger oil R:P ratio tend to result in a smaller gas R: P ratio, meaning that as the global energy system weans itself away from oil, it tends to increase its reliance on natural gas.

The impacts of the D&D shocks compared to those of the R&D shocks presented in Section 2.2 depend on a number of factors, including the stage of development each technology is in, and the extent to which the broader energy market is compatible for a specific technology – that is, whether the necessary complementary systems exist, particularly infrastructure, and whether there is a market for the technology output. The next section examines whether these two types of technology policies can be combined in supporting ways to create additional opportunities to realise sustainability objectives.

Figure 2-9: Impact of D&D shocks on global oil and gas resource-to-production ratios in 2060, relative to baseline



Note: For abbreviations of the technologies see Table 2-1 on page 400. Impacts are reported in a way that is consistent with the change in the underlying indicator, so that a negative impact means the indicator decreased, and a positive impact means the indicator increased.

2.4. Combined D&D and R&D shocks

In our discussion of the results of orthogonal R&D and D&D shocks, we noted on a number of occasions that a shock may result in a limited or undesirable impact on sustainability because of constraints on other parts of the energy system. In some ways this is not surprising because a single shock cannot be expected to direct the development of the entire energy system onto a more sustainable path, and although it may address barriers to the adoption of one technology, it may in doing so raise barriers for other technologies.

Some of the best examples of the potential undesirable effects of a shock were observed for many of the D&D shocks which displaced hydrogen fuel cell electricity generation, effectively locking out this technology and resulting in poorer sustainability outcomes. This outcome can be partly explained by constraints on the learning and deployment rates of the fuel cell technology – that is, this technology is only locked out because its learning and deployment rates restrict its ability to recover from the delay in learning-by-doing caused by the shock. One way to circumvent some of these other constraints is to target multiple parts of the energy system with simultaneous shocks, effectively applying a more consistent technology and policy strategy. In this section we present one set of simultaneous D&D and R&D shocks to explore the potential for well-targetted technology support to transform the energy system and lead to improved sustainability outcomes. These shocks are defined and applied exactly as outlined at the start of this Section.

In an attempt to identify shocks which may potentially have a greater impact on the sustainability indicators of interest, we selected the R&D shock with the greatest impact as the starting point for this analysis. This shock, applied to the fuel cell technology component, was observed to have the largest positive impact on a number of the sustainability indicators (see Section 2.2). In this analysis we then combine with this R&D shock each of the D&D shocks to ascertain whether the positive impact can be enhanced by targeting directly or indirectly related technologies. The effect on selected climate change and security of supply indicators are outlined below, again in the form of impacts.

2.4.1. Energy system development and atmospheric GHG concentrations

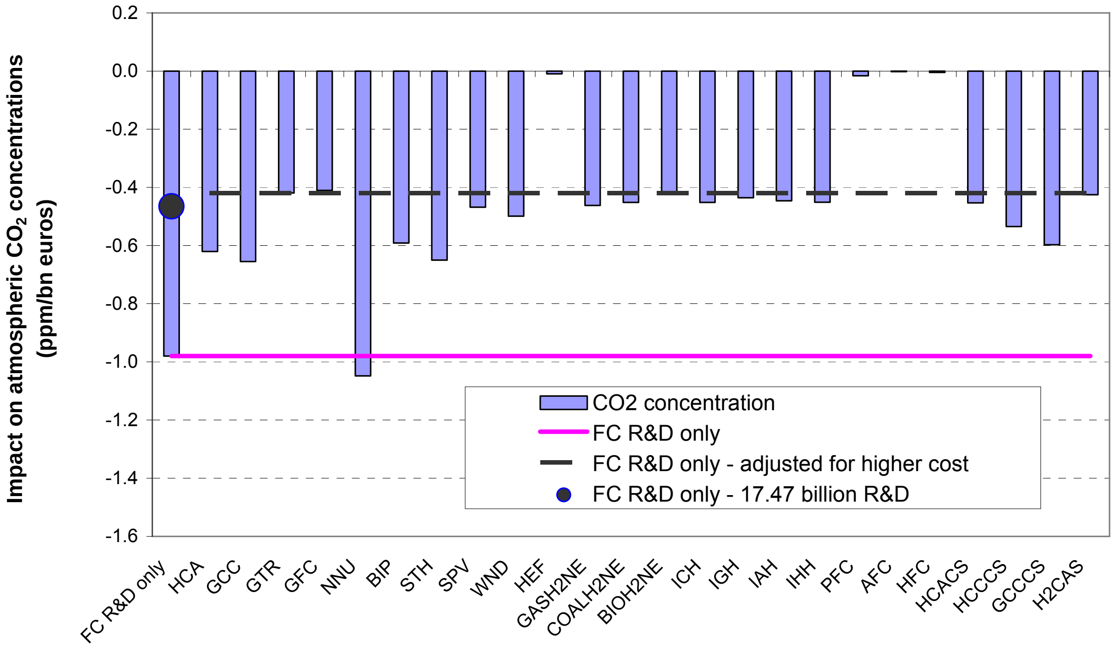
The impact on atmospheric CO_2 concentrations of the combined R&D and D&D shocks is presented in Figure 2-10. Again, this figure shows the impact per total shock expenditure – combining R&D expenditure of €7.47 billion and D&D expenditure of €10 billion – on this sustainability indicator. For comparison, Figure 2-10 also includes the impact of the R&D shock alone. The most noticeable result is that the impact of the combined shocks is generally lower than that of the independent R&D shock. However, it should also be noted that applying a similar-sized R&D shock to the fuel cell technology alone (i.e., €17.47 billion) has a lower impact per euro because of saturation of potential learning-by-searching (shown by the large dot in Figure 2-10). Moreover, it should be remembered that the total investment is around 130 percent greater under the combined shocks, and so the absolute change in the indicator is higher in a number of cases under the combined shock, even though the "impact" is lower. This is illustrated in Figure 2-10 where the dashed line shows what the impact would be if the incremental D&D shock had no effect on concentrations.[30]

Figure 2-10 shows that the greatest impact is observed with the combined fuel cell R&D and advanced nuclear D&D shock. This is particularly interesting because this D&D shock alone resulted in an <u>in</u>crease in CO_2 concentrations of around 0.6 ppm/€bn (see Figure 2-7), whereas the combined shock results in a decrease of over 1 ppm/€bn. The increase in concentrations under the single shock was discussed in Section 2.3.1, and can be attributed to crowding out of fuel cell generation by additional advanced nuclear generation. By contrast, the combined shock provides sufficient support for fuel cells such that advanced nuclear does not displace and lock out hydrogen fuel cell generation, but instead displaces additional coal-fired generation. In addition, the combined fuel cell R&D shock results in the adoption and rapid penetration of fuel cells in transport applications, as was observed for this shock alone (Section 2.1). This example highlights the potential benefits of a co-ordinated strategy aimed at low-emissions technologies, particularly for overcoming unhelpful competition between low-emissions sources.

---

[30] Interestingly, the dashed line is at roughly the same level as the large dot representing the impact with higher R&D expenditure. This implies that the impact of this R&D shock is already largely saturated.

Figure 2-10: Impact of D&D shocks combined fuel cell R&D shock on atmospheric CO_2 and CH_4 concentrations in the year 2100, relative to baseline



Note: For abbreviations of the technologies see Table 2-1 on page 400. Impacts are reported in a way that is consistent with the change in the underlying indicator, so that a negative impact means the indicator decreased, and a positive impact means the indicator increased.

In Section 2.3, the advanced nuclear generation D&D shock was not the only one to displace and lock out fuel cells, leading to higher CO_2 concentrations. This result was also seen for D&D-only shocks applied to biomass, solar thermal and gas combined cycle generation (which increased CO_2 concentrations by more than 1.5 ppm/€bn, see Figure 2-7). However, Figure 2-10 shows that when combined with the fuel cell R&D shock, all of these D&D shocks now reduce concentrations because they no longer lock out hydrogen fuel cell generation. These shocks now produce an impact that is more intuitive, considering they provide support for low-emissions generation technologies. Similarly, the D&D shock applied to the advanced IGCC technology (HCA), although more emissions intensive than other sources, now improves emissions because it displaces almost entirely conventional coal generation, instead of fuel cells (which was the case when the D&D shock was applied independently, as shown in Section 2.3). Taken together, these examples highlight the importance of developing and implementing a co-ordinated and reinforcing (as opposed to competitive) technology strategy for realizing sustainability objectives.

Interestingly, combining the fuel cell R&D shock with a D&D shock targeted at directly related technologies such as gas or hydrogen fuel cell generation (GFC, HEF) has no additional impact, or results in a relative worsening (increase) in atmospheric concentrations in the case of the D&D shock to hydrogen fuel cell generation. These results can be explained by appreciating the interplay between different fuel cell technologies, and the limited availability of hydrogen.

Looking first at the gas fuel cell generation technology, a D&D shock reinforces the impact of the R&D shock on the competitiveness of fuel cell electricity generation. This results in much greater output from fuel cell generators (than under the R&D shock alone). Moreover, the D&D shock also provides a slight competitive edge to stationary fuel cells over mobile fuel cells, which is sufficient to render more attractive the use of hydrogen in stationary generation rather than transport. As an overall consequence, the impact on atmospheric CO_2 concentrations from a greater share of electricity generation from low-emissions fuel cells (compared to under the R&D shock alone) is offset by the failure of fuel cells to penetrate significantly the transport market.

In the case of the hydrogen fuel cell (HEF) D&D shock, although it provides some learning-by-doing benefits initially, its impact on the energy system is small because of the very limited availability of hydrogen production and distribution infrastructure early in the century. However, the one impact of this combined shock is to provide enough competition for the small quantities of hydrogen that are available early in the century to stifle the emergence of a fuel cell powered transportation sector. As a consequence, this D&D shock results in almost no additional fuel cell generation compared to the baseline scenario, and no deployment of fuel cells in transportation. That is, it undermines the positive effects of the R&D shock on CO_2 concentrations, even though both shocks support very similar technologies.

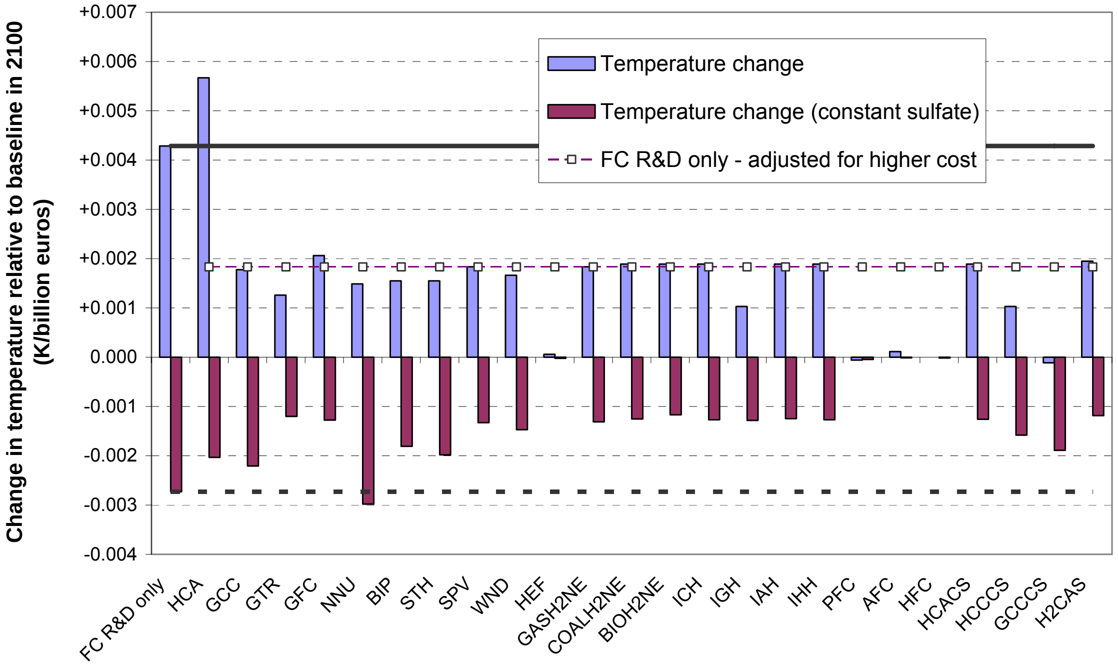
A similar result is observed when the fuel cell R&D shock is combined with D&D shocks to any of the fuel cell transportation technologies (PFC, AFC and HFC). These technologies are very expensive at the time the D&D shock is applied, so deployment cannot establish the necessary critical mass to support the early emergence of a fuel cell-based transport system. However, these shocks provide some learning-by-doing experience with fuel cells, which is sufficient for the stationary technologies to gain a relative competitive advantage to mobile fuel cell applications. To put this another way, a little support is required to make mobile fuel cells competitive with other transport technologies, but too much D&D support at the “wrong” time appears to make the use of hydrogen in stationary fuel cells more attractive. Because there is more potential demand for hydrogen than there is supply, the less competitive applications (in transport) are displaced by alternative technologies – in this case, by hybrids and alcohol fuels. This result may be reinforced by the requirement for possible additional hydrogen distribution requirements for mobile fuel cell applications. In Figure 2-10, we see that there is almost no impact on atmospheric CO_2 concentrations relative to the baseline scenario. It is important to emphasise that this appears to be quite a complex result, with a number of reinforcing and countervailing forces operating simultaneously, so these results can only provide an initial guide as to the possible consequences of this combination of technology support policies.

The only other significant results in Figure 2-10 relate to the demonstration and deployment shocks applied to post-combustion carbon capture from coal and gas electricity generation (HCCCS, GCCCS). In the case of both of these technologies, the impact of the combined R&D-D&D shock appears to be roughly equal to weighted average of the separate impacts. This implies that these shocks are largely independent, even though we have seen that the fuel cell R&D shock displaces some coal-fired electricity generation.

2.4.2. Temperature

The impact on temperature change of the combined R&D and D&D shocks is presented in Figure 2-11. Once again, when the effect of the shock on emissions of oxides of sulfur (SO_x) is excluded, the impact on temperature closely mirrors the impact on atmospheric CO_2 concentrations, which is not surprising. However, a more complex picture emerges when the overall impact on temperature is examined. Figure 2-11 shows that the R&D shock alone has close to the worst impact on global average temperature in 2100, under the assumptions applied here. However, as discussed above, this result is largely due to the fact that total expenditure on R&D and D&D is 130 percent larger under the combined shock than for the R&D-only shock, and SO_x emissions do not change by anywhere near as much. In Figure 2-11 we also show what happens to the impact of the R&D shock if we simply assume a larger expenditure, illustrated by the dashed line with squares. Comparing this with the reported impacts for the combined shocks shows that in many cases the additional D&D expenditure makes only a very small change to the actual temperature. This is partly because many shocks have little additional impact, as was seen for emissions in Figure 2-10, but is also partly explained by the aversion to coal under the assumptions applied here, particularly the climate policy. This aversion means that any shock will tend to reduce coal consumption (especially using conventional technologies), reducing CO_2 and, in many cases, SO_x as well, which tends to balance the impact on forcing and temperature change.

Figure 2-11: Impact of D&D shocks combined fuel cell R&D shock on global average temperature in the year 2100, realtive to baseline



Note: For abbreviations of the technologies see Table 2-1 on page 400. Impacts are reported in a way that is consistent with the change in the underlying indicator, so that a negative impact means the indicator decreased, and a positive impact means the indicator increased.

One important exception, of course, is the D&D shock to IGCC coal generation, which supports coal consumption while at the same time significantly reducing SO_2. However, the D&D shock to IGCC (HCA), in combination with the R&D shock to fuel cells, is far more effective at displacing conventional coal than either shock alone. As a consequence, CO_2 emissions and forcing are lower but SO_x emissions are much lower, and this manifests as a higher average global temperature in Figure 2-11.

It is interesting to contrast this result with some of the other technology shocks that result in a relative reduction in global temperature. Looking at both indicators of temperature change (with and without changes in sulfate forcing), the D&D shock applied to the gas combined cycle carbon capture technology is the only one to improve both, which also occurred when this D&D shock was applied without the gas fuel cell R&D shock. However, the impact on constant-sulfate temperature is about the same under this combination of shocks as it is for the IGCC-fuel cell combination discussed in the previous paragraph, even though the latter results in the highest temperature when SO_x emissions are considered. The choice of which is the most appropriate indicator to target has been discussed in previous sections, and the consequences of this choice is starkly illustrated by the choice between these two technology support combinations.

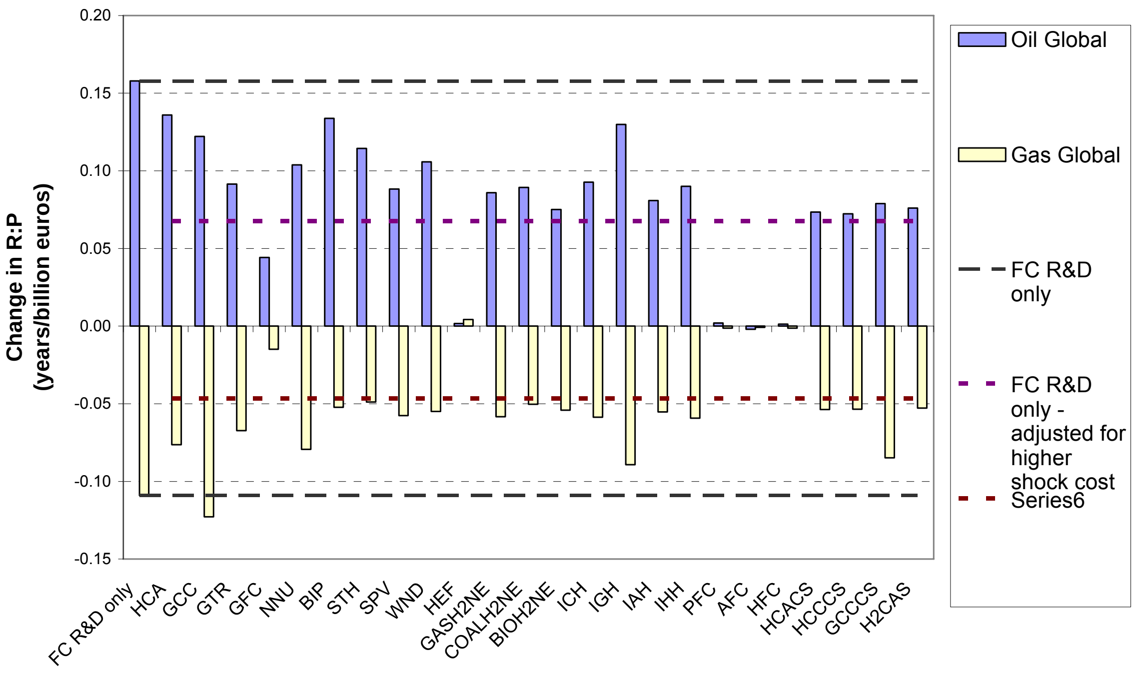
Importantly, however, there are other shock combinations which have an even greater impact on temperature with constant sulfate, such as the combined fuel cell R&D and advanced nuclear D&D shock. This shock also results in a *relative* improvement in the impact on global temperature when changes in SO_x emissions are also considered. Other combined shocks that improve both indicators relative to the single R&D shock are those targeted at gas combined cycle (GCC), solar thermal (STH) and biomass (BIP) generation, and carbon capture from conventional coal generation (HCCCS). Most of the other combined technology shocks behave similarly to the D&D-alone shocks, although starting from a different baseline.

2.4.3. Security of energy supply

We now turn to the impacts on indicators of security of energy supply. As mentioned earlier in this report, the resources-to-production ratio used as an indicator of energy security differs from the conventional reserves-to-production ratio (BP 2004) in that it is a long-term indicator of sustainable resources use which can only be influenced through changes in consumption, unlike the reserves-to-production ratio which can be increased by identifying and reclassifying resources.

Under the shocks examined here, impacts on the resources-to-production ratio for oil in the year 2060 are in almost all cases positive or zero, as shown in Figure 2-12: . However, this is not surprising considering that the R&D shock alone elicits the same or a stronger response, as do many of the D&D-only shocks (Sections 2.1 and 2.3.2). In almost all cases, these shocks are able to displace oil consumption largely by increasing gas consumption. As briefly mentioned earlier, under the assumptions used in these scenarios, gas is a very attractive fuel. Accordingly, the additional pathways created by the shocks that allow the efficient use of gas to displace less attractive fuels such as coal are exploited. Consequently, as shown in Figure 2-12: , this means that the incremental effect on the indicator of all but five of the D&D shocks on gas security is negative (refer to the dotted line in Figure 2-12: indicating the level of the R&D-only shock after adjusting for the additional cost of the D&D shocks).

Figure 2-12: Impact of D&D shocks combined fuel cell R&D shock on global oil and gas resource-to-production ratios in 2060, relative to baseline



Note: For abbreviations of the technologies see Table 2-1. Impacts are reported in a way that is consistent with the change in the underlying indicator, so that a negative impact means the indicator decreased, and a positive impact means the indicator increased.

The five combined D&D shocks that improve gas security (while worsening oil security) relative to the R&D-only shock have been discussed earlier in Section 2.3.2, and comprise entirely shocks targeted at the fuel-cell technologies (GFC, HEF, PFC, AFC, HFC). The impact of these shocks is small because they ultimately support stationary hydrogen fuel cell generation, but are unable to stimulate additional hydrogen production, and so these technology support scenarios do not diverge substantially from the baseline scenario (with the exception of the shock to stationary gas fuel cell generation which supports additional deployment of this technology, relative to the baseline).

Since all other combined shocks worsen gas security relative to the R&D-only shock, we can only attempt to identify those technology support combinations that have the smallest additional negative effect while maximizing oil security. Of course, the relative importance of these sustainability indicators should determine the weighting applied to maintaining the lifetime of either resource. However, it should be noted that the oil R:P ratio is generally lower than the gas R:P (see Section 2.2.3) under the assumptions applied here, so declines in the oil ratio may be more likely to lead to the emergence of more extreme vulnerabilities to supply disruption. However, the fact that gas is an increasingly important fuel for a large part of the 21st century under these scenarios, may mean that decreasing supply security of this resource will have larger and more extensive consequences.

Looking at Figure 2-12: , the combined shocks that result in the best outcomes for oil security are those targeted at electricity generation from IGCC coal (HCA), gas combined cycle turbines (GCC), biomass, solar thermal, wind and nuclear sources, and gas hybrid vehicles (IGH). However, the shocks targeted at gas combined cycle generation and hybrids results in a significant worsening of gas security, which is not unexpected considering these are gas-based technologies, and should only be pursued if the impact on gas security of supply is considered to be managable. Of the remaining technologies, the renewable forms of generation (BIP, STH, WND) appear to perform well on both indicators, with biomass generation having the largest impact on the oil R:P.

2.5. Discussion, conclusions and summary

This section has examined the long-term impact on indicators of sustainable development of a number of technology support policies. The measures of sustainable development of interest include indicators of climate change – including atmospheric concentrations of greenhouse gases, temperature change and sea-level rise – and measures of security of energy supply for oil and gas. The technology support policies investigated in this analysis include energy research and development (R&D) and demonstration and deployment (D&D) programs.

The analysis was conducted using the modeling framework developed at IIASA-ECS for the SAPIENTIA project, as described in Turton and Barreto (2003), and updated to incorporate additional material from other SAPIENTIA partners (including Kouvaritakis and Panos 2005). The main elements of this framework comprise the “bottom-up” energy-systems ERIS model and the climate model MAGICC. The ERIS model incorporates technological learning and spillovers, and extensive energy and non-energy GHG abatement opportunities.

Importantly, the impact of technology support policies and measures using this framework is strongly influenced by assumptions about the baseline development of the energy system, and policy environment. A number of critical elements in the baseline scenario must be considered when interpreting the results of this analysis. These include a climate change policy, which itself encourages the adoption of a number of technologies with a positive impact on the sustainability indicators of interest. Other important features include the assumed levels of resources, limits on the deployment rates of new technologies, and assumptions about R&D expenditure and energy demand.[31] In many cases, these critical assumptions can be expected to have more influence on the

---

[31] Assumptions about the application of other related technologies and policies, such as those aimed at reducing sulfate emissions from combustion, may also have an important bearing on the results. This particular example is discussed later in this section.

development of the energy system than the technology policies. Conversely, changing these assumptions, such as by incorporating a more stringent climate policy, will redirect the development of the energy system, and may result in other technologies becoming more important, and thus possible targets for support.

In the baseline scenario used in this analysis, the main energy system developments over the century include a transition to natural gas-based electricity generation before a strong shift to nuclear and renewable forms of electricity generation. In addition, fuel cells play an increasingly important role in electricity generation in this baseline scenario and are among the fastest growing technologies at the end of the century. Consequently, hydrogen becomes an important energy carrier, although other fuels remain important. In transportation, hybrid engines, natural gas and alcohol fuels all play an important role (although fuel cells do not). Greenhouse gas emissions peak in 2070, and atmospheric CO_2 concentrations rise to 700 ppm by 2100 (and are still increasing) under this scenario.

To examine the potential significance and impact of additional support for energy R&D under this baseline scenario, we analysed the impact of the «R&D Doubling» and Zero "R&D" scenarios. The «R&D Doubling» scenario – involving a doubling of government energy R&D until 2050 – resulted in a transformation of some key elements of the energy system, illustrating the potential impact of technology support policies. Specifically, this «R&D Doubling» scenario provided sufficient support to fuel cells and related technologies to lead to deployment of, and eventual domination of the transport sector by fuel cell vehicles (instead of hybrids). Furthermore, this «R&D Doubling» scenario also changed the electricity sector, although less significantly, by facilitating additional generation from gas combined cycle generation and a shift from hydrogen fuel cells to gas fuel cells (given that much of the available hydrogen was now consumed in the transport sector). This resulted in a displacement of coal-fired electricity generation, lower GHG emissions and improved outcomes on a number of sustainability indicators.

In contrast, the «Zero GERD» scenario resulted in relatively little change in the energy system compared to the baseline scenario. This appears to raise two conflicting conclusions – firstly, that under the assumptions here government R&D support can have a significant and far-reaching impact on energy system development («R&D Doubling» scenario), while other factors influencing the development of the energy system, including the climate policy and resource constraints, may have a much larger influence than public energy R&D support («Zero GERD» scenario). These apparently contradictory results imply that for government R&D support to be effective it needs to be compatible with the broader policy, technology and resource environment. Moreover, even taking the results of the «Zero GERD» scenario at face value does not necessarily imply that there is no place for government energy R&D, since even though such policies may have only a small influence on the direction of energy system development, they can still have an important influence on cost.

The idea that R&D support needs to be compatible with other constraints on the energy system and policy variables was explored by targeting support to key technologies in the form of R&D "shocks". This exercise reinforced the conclusion that there are only limited opportunities for public R&D support to be effective in transforming the development of the global energy system, and this support needs to be compatible with other factors directing development. Specifically, almost all of the technology-specific R&D shocks had almost no effect on the development of the energy system – which is consistent with the result observed under the «Zero GERD» scenario. However, the most significant exception was R&D support for the generic fuel cell technology used in both stationary and mobile applications. This shock was sufficient to shift the development of the energy system as a whole onto a path very similar to that under the «R&D Doubling» scenario, but for a fraction of the cost, indicating that a single well-targetted technology support program can substantially change the development path followed by the global energy system.

In many was it is not surprising that very few shocks were observed to have a significant impact on energy system development. This can be understood if one remembers that this scenario assumes a climate change policy, so alternative technology options can be thought of as different greenhouse gas abatement opportunities with different costs. The climate policy is modeled as a GHG tax, and all of the technology options with an abatement cost of below the tax rate are exploited under the baseline scenario. Accordingly, under the assumptions applied here an R&D shock (or support program) can only change the technology development path if it shifts the cost of an abatement opportunity from above to below the GHG tax rate. This is affected by technology characteristics, but within the mix of technologies examined here, it is not surprising that this occurred infrequently. For technology options that were already attractive, the R&D shocks only help to reduce overall energy system costs – that is, there is still a return on R&D investment, despite this investment having little or no impact on the indicators of sustainable development. On the other hand, R&D shocks targeted at technologies that are unattractive, and remain unattractive after the shock, have effectively no impact, but may represent an important part of a hedging strategy against uncertainty regarding the necessary stringency of future climate change mitigation targets.

This again highlights the importance of the baseline scenario assumptions. Were we to assume a less or more stringent climate change policy, this would change the suite of technologies that are competitive under the baseline scenario, and move the critical threshold that determines whether an R&D shock has any significant effect on the energy system. This further reinforces the notion that technology policy needs to be designed and implemented in a way that complements and enhances the existing policy environment. As mentioned, uncertainty regarding the potential policy environment warrants an effective technology policy hedging strategy, in which a suite of technologies are targeted initially, and as policy uncertainty is resolved technology support programs become increasingly focused.

One element of such a comprehensive and complementary technology policy may require combining technology-push with market-pull, to accelerate technology deployment and realise positive impacts on sustainability indicators. The role of technology demonstration and deployment (D&D) policies in achieving sustainable development objectives was also explored in this analysis. These D&D technology policies – again applied in the form of a "shock" in the base year – were examined both separately and in combination with R&D policies.

When pursued separately, some D&D policies were observed to have the potential to improve a number of indicators of sustainability. However, under the assumptions and baseline scenario used here, in many cases these D&D shocks "crowded out" other technologies, resulting in poorer sustainability outcomes. Specifically, most of the D&D shocks applied to electricity generation technologies resulted in one of the most successful low-emissions technologies in the baseline scenario – fuel cell electricity generation – missing a critical window of opportunity. The high level of support provided to other technologies by the D&D shock effectively lock out a nascent fuel cell generation industry, which is unable to penetrate the market later in the century because critical learning opportunities have been missed. The alternative technologies receiving the D&D support, including zero emissions technologies such as nuclear and renewable generation, make an initially positive contribution to some of the sustainability indicators, but are ultimately limited by technical and/or resource constraints, leading to a longer and larger reliance on less sustainable technologies. This illustrates a significant danger associated with supporting certain technologies without considering the potential limitations they may face and the possible lock-out over the longer term of more promising technologies. Accordingly, support programs for technologies need to be pursued in a way that is complementary rather than competitive to the development of other technologies likely to contribute to the achievement of sustainability objectives.

Combining R&D and D&D may be one effective way of pursuing a complementary technology support strategy. This analysis demonstrated that technology lock-out of fuel cell generation could be avoided if R&D support was provided to fuel cells while D&D support provided to other technologies. This more integrated technology policy addressed multiple barriers to technology adoption in a way that was reinforcing and complementary. Consequently, the largest improvements in a number of sustainability indicators were observed under combined policies and, more importantly, high impacts (per euro) were also maintained. The most effective combined shock explored in this analysis on a number of sustainability indicators comprised R&D support for fuel cells and deployment support for advanced nuclear generation. These together accelerated the deployment of a zero-emissions and potentially large-scale generation technology (advanced nuclear), while supporting the critical early development stages for fuel cell technologies, allowing them to make a large contribute in the future energy system in both electricity generation and transport. Demonstration and deployment shocks targeted at other low-emissions technologies also resulted in incremental improvements in sustainability indicators when combined with the R&D shock. Not surprisingly, this shows that technology policies can be most effective at realizing sustainability objectives when they combine complementary and reinforcing elements.

This is particularly relevant to the hydrogen-related technologies examined in this analysis, where D&D or R&D shocks targeted at individual hydrogen production or consumption technologies had relative little impact. Apart from the need to address barriers specific to each technology, these results illustrate the requirement for all elements of a hydrogen-based energy system to be in place before potential benefits can be fully realised. Accordingly, considering the need for co-ordination and the large level of investment and potential risk associated with developing the infrastructure required across the hydrogen energy chain, there is potentially a very significant role for government support and deployment programs.

Importantly, however, many of the results of this analysis imply that the relative importance given to different sustainability objectives may have a bearing on the choice of targets for technology support. For instance, in many cases the R&D and D&D programs examined here supported technologies that were able to displace coal-based energy systems, thereby reducing both CO_2 and SO_x emissions. As a consequence although many of these technology policies reduced atmospheric GHG emissions, they resulted in a small increase in temperature because the negative radiative forcing from sulfate aerosols was reduced. This potentially leads to the perverse conclusion that climate change indicators can be improved by maximising SO_x emissions (probably by supporting coal-based technologies). However, taking a long-term perspective it may be reasonable to assume that SO_x-reduction policies will be implemented as part of the pursuit of other environmental goals, and so lower weighting should be attached to the effect of sulfate aerosols on temperature change in the pursuit of long-term climate change mitigation.

Another area where a potential trade-off may occur is pursuit of both climate change mitigation and maintenance of security of energy supply. Again, however, this depends on the relative importance given to different indicators. As discussed in Section 2.4.3, oil is globally less abundant than natural gas, so the fact that many of the D&D and R&D shocks that produced positive climate change impacts also improved oil security at the expense of gas security of supply may be considered a reasonable trade-off. However, because gas becomes an increasingly important fuel for a large part of the 21st century under these scenarios, it may be more important to protect the longevity of this resource, since any supply disruption may have larger and more extensive consequences. Appreciating such potential synergies (such as between climate change mitigation and oil security) and trade-offs (such as gas security) are important for designing an appropriate integrated technology policy strategy (see Turton and Barreto 2005).

References

Barreto, L., Kypreos, S., 2000: A post-Kyoto analysis with the ERIS model prototype. Int. J. of Global Energy Issues 14(1/2/3/4):262-280.

Barreto, L., Kypreos, S., 2004: Endogenizing R&D and market experience in the “bottom-up” energy-systems ERIS model. Technovation 24(8), 615-629.

Barreto, L., Turton, H., 2005: Impact of alternative policy instruments on climate change and security of energy supply indicators: an analysis for MINIMA-SUD: Report to the EC-sponsored MINIMA-SUD Project, Interim Report IR-05-002, International Institute for Applied Systems Analysis, Austria.

BP, 2004, Energy in focus, Statistical review of world energy 2004, BP, http://www.bp.com/subsection.do?categoryId=95&contentId=2006480.

DOC (US Department of Commerce), 1999: The Effect on the National Security of Imports of Crude Oil and Refined Petroleum Products. Bureau of Exports Administration. US Department of Commerce, November, 1999.

EC (European Commission), 2001: Towards an European Strategy for the Security of Energy Supply. Green Paper of the European Commission. Brussels, Belgium.

Hasselmann, K., Latif, M., Hooss, G., Azar, C., Edenhofer, O., Jaeger, C.C., Johannessen, O.M., Kemfert, C., Welp, M., Wokaun, A., 2003. The Challenge of long-term Climate Change. Science 302, 1923-1925. December12, 2003.

Hoffert, M., Volk, T., Caldeira, K., Perkins, L.J, Benford, G., Criswell, D., Green, C., Lightfoot, H.D., Herzog, H., Jain, A.J., Schlessinger, M., Kheshgi, H., Lackner, K., Mauel, M., Lewis, J., Manheimer, W., Mankins, J.C., Wigley, T, 2002: Advanced Technology Paths to Global Climate Stability: Energy for a Greenhouse Planet. Science 298, 981. November 1, 2002.

IEA (International Energy Agency), 2001: Towards a Sustainable Energy Future. International Energy Agency (IEA), Paris, France.

IPCC (Intergovernmental Panel on Climate Change), 2001a: Climate Change 2001: Mitigation, Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK. 700 pp, ISBN: 0521015022.

IPCC (Intergovernmental Panel on Climate Change), 2001b: Summary for Policymakers (SPM). In: J. T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P. J. van der Linden and D. Xiaosu (eds.), Climate Change 2001: The Scientific Basis, Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, UK. pp 944.

Kemp, R., 1997: Environmental Policy and Technical Change: A Comparison of the Technological Impact of Policy Instruments. Edward Elgar. Cheltenham, UK.

Kouvaritakis, N. Panos, V., 2005: Modelling the two factor learning curve equations: guidelines on implementation, Report for the SAPIENTIA project, E3M Lab, School of Electrical and Computer Engineering, National Technical University of Athens, 4 March

Kypreos, S., Barreto, L., Capros, P. Messner, S., 2000: ERIS: A model prototype with endogenous technological change. Int. J of Global Energy Issues 14(1/2/3/4):374-397.

Messner, S., 1998: IIASA Maquette Model Prototype on Endogenized Technological Learning. TEEM Project. International Institute for Applied Systems Analysis. Laxenburg, Austria.

Nakićenović, N., 1997: Technological Change as a Learning Process. Paper presented to the IIASA Induced Technology Workshop, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Nakićenović, N., 2003: Climate Change Scenarios and Mitigation Technologies. Paper presented to the World Climate Change Conference. Moscow, Russia. September 29 - October 3, 2003.

Rogner, H.H., 1997: An assessment of world hydrocarbon resources, Annual Review of Energy and Environment 22:217-262.

Turton, H., Barreto, L. 2005. Long-term security of energy supply and climate change, Energy Policy (forthcoming)

Turton, H., Barreto, L., 2003: The bottom-up energy-systems ERIS model: Extensions for SAPIENTIA. Report to the EC-sponsored SAPIENTIA Project. International Institute for Applied Systems Analysis. Laxenburg, Austria. December, 2003.

Wigley, T.M.L., 2003: MAGICC/SCENGEN 4.1: Technical Manual, National Center for Atmospheric Research, Colorado, USA, October 2003.

Wigley, T.M.L., Raper, S.C.B., 1997: Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC Version 2.3.), The Climate Research Unit, University of East Anglia, UK.

APPENDIX Table A1. Impact of technology learning on capital costs, «Zero GERD» scenario

Group	Technology	Abbreviations	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
			€99/kW										
Electricity generation technologies	Conventional Coal	HCC	1,219	1,214	1,161	1,121	1,077	1,045	1,018	995	974	958	947
	Integrated Coal Gasification Combined Cycle (IGCC)	HCA	1,436	1,404	1,380	1,353	1,324	1,286	1,253	1,244	1,236	1,228	1,222
	Oil Conventional Thermal	OLC	1,108	1,070	1,057	1,056	1,056	1,056	1,056	1,056	1,056	1,056	1,056
	Gas Turbine Combined Cycle	GCC	548	536	524	517	513	510	508	508	508	507	507
	Gas Conventional Thermal	GSC	986	943	922	904	895	892	890	890	890	890	890
	Gas Turbine Open Cycle	GTR	384	374	358	346	338	332	328	327	326	325	325
	Gas Fuel Cell (generic stationary)	GFC	11,755	6,479	3,510	1,384	589	413	294	233	205	181	164
	Nuclear (2nd and 3d gen.)	NUC	2,765	2,671	2,334	2,073	1,906	1,840	1,790	1,771	1,759	1,746	1,737
	New Nuclear (4th gen.)	NNU	8,555	8,416	8,256	8,092	7,017	6,051	5,205	4,457	3,829	3,284	2,833
	Biomass	BIP	2,477	2,108	2,037	1,988	1,942	1,901	1,868	1,868	1,868	1,868	1,868
	Large Hydro	HYD	3,227	3,144	3,065	2,932	2,748	2,526	2,383	2,312	2,287	2,270	2,251
	Solar Thermal Power Plant Cylindro-Parabolic	STH	3,111	3,015	2,893	2,751	2,597	2,448	2,311	2,300	2,289	2,279	2,276
	Building Integrated PV	SPV	6,385	4,933	4,193	3,511	2,951	2,288	1,958	1,883	1,879	1,878	1,869
	Wind Turbines	WND	1,061	986	920	853	802	768	743	738	735	733	731
	Hydrogen Fuel Cell (generic stationary)	HEF	11,755	6,479	3,510	1,384	589	413	294	233	205	181	164
			€99/m3d										
Hydrogen production technologies	Hydrogen from Gas Steam Reforming (large scale)	GASH2NE	46	45	36	36	36	36	36	36	36	36	36
	Hydrogen from Coal Partial Oxidation	COALH2NE	117	112	107	102	96	90	85	84	83	81	80
	Hydrogen from Biomass Pyrolysis	BIOH2NE	122	116	106	99	95	90	86	85	83	81	79
			€99/vehicle										
Passenger car technologies	Conventional ICE Passenger Car	ICC/ICG/ICA	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000
	Hybrid Passenger Car	ICH/IGH/IAH	7,700	6,083	5,599	5,255	5,019	4,970	4,931	4,912	4,900	4,891	4,884
	Hydrogen ICE-Hybrid Passenger Car	IHH	11,000	9,383	8,899	8,555	8,319	8,270	7,606	7,565	7,543	7,530	7,513
	Reformer-Fuel Cell Passenger Car	PFC/AFC	590,200	379,150	260,418	175,360	143,574	136,528	131,760	129,304	128,208	127,243	126,541
	Hydrogen Fuel Cell Passenger Car	HFC	472,600	261,550	142,818	57,760	25,974	18,928	13,705	11,233	10,130	9,162	8,453
			€99/toe input per year										
Carbon capture technologies	Pre-Combustion CO_2 capture (IGCC)	HCACS	31	31	10	10	10	10	10	10	10	10	10
	Post-Combustion CO_2 capture (Conventional Coal)	HCCCS	52	52	24	22	20	20	20	20	20	20	20
	Post-Combustion CO_2 capture (GCC)	GCCCS	31	31	11	11	11	11	11	11	11	11	11
			€99/m3d										
	Pre-Combustion CO_2 capture (Hydrogen Production)	H2CAS	68	68	68	68	67	66	65	64	63	62	61

Table A2. Impact of technology learning on capital costs, «R&D Doubling» scenario

Group	Technology	Abbreviations	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
			€99/kW										
Electricity generation technologies	Conventional Coal	HCC	1,219	1,214	1,161	1,121	1,077	1,044	1,017	994	974	958	950
	Integrated Coal Gasification Combined Cycle (IGCC)	HCA	1,436	1,349	1,300	1,251	1,208	1,163	1,127	1,121	1,116	1,110	1,106
	Oil Conventional Thermal	OLC	1,108	1,069	1,056	1,054	1,053	1,052	1,051	1,051	1,051	1,051	1,051
	Gas Turbine Combined Cycle	GCC	548	535	523	516	512	509	507	507	506	506	506
	Gas Conventional Thermal	GSC	986	941	919	900	889	883	879	879	879	879	879
	Gas Turbine Open Cycle	GTR	384	373	357	344	336	330	326	325	324	323	323
	Gas Fuel Cell (generic stationary)	GFC	11,755	5,234	695	152	89	57	50	50	50	50	50
	Nuclear (2nd and 3d gen.)	NUC	2,765	2,436	2,058	1,869	1,791	1,763	1,742	1,733	1,727	1,720	1,715
	New Nuclear (4th gen.)	NNU	8,555	6,693	5,573	4,648	3,483	2,643	2,029	1,742	1,502	1,299	1,296
	Biomass	BIP	2,477	2,056	1,979	1,926	1,880	1,843	1,814	1,814	1,814	1,814	1,814
	Large Hydro	HYD	3,227	3,143	3,063	2,929	2,747	2,524	2,382	2,312	2,285	2,269	2,250
	Solar Thermal Power Plant Cylindro-Parabolic	STH	3,111	2,784	2,523	2,298	2,119	1,983	1,877	1,871	1,865	1,860	1,858
	Building Integrated PV	SPV	6,385	4,346	3,400	2,705	2,263	1,906	1,728	1,696	1,689	1,686	1,683
	Wind Turbines	WND	1,061	932	850	786	744	719	701	698	696	695	694
	Hydrogen Fuel Cell (generic stationary)	HEF	11,755	5,234	695	152	89	57	50	50	50	50	50
			€99/m3d										
Hydrogen production technologies	Hydrogen from Gas Steam Reforming (large scale)	GASH2NE	46	45	34	34	34	34	34	34	34	34	34
	Hydrogen from Coal Partial Oxidation	COALH2NE	117	107	101	95	90	84	79	78	77	76	75
	Hydrogen from Biomass Pyrolysis	BIOH2NE	122	113	103	97	93	88	85	83	81	79	78
			€99/vehicle										
Passenger car technologies	Conventional ICE Passenger Car	ICC/ICG/ICA	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000	3,000
	Hybrid Passenger Car	ICH/IGH/IAH	7,700	5,685	5,295	5,053	4,993	4,946	4,909	4,896	4,890	4,887	4,886
	Hydrogen ICE-Hybrid Passenger Car	IHH	11,000	8,985	8,595	7,671	7,528	7,418	7,321	7,255	7,217	7,191	7,173
	Reformer-Fuel Cell Passenger Car	PFC/AFC	590,200	329,345	147,784	126,084	123,567	122,293	122,000	122,000	122,000	122,000	122,000
	Hydrogen Fuel Cell Passenger Car	HFC	472,600	211,745	30,184	7,988	5,411	4,091	3,754	3,716	3,692	3,675	3,663
			€99/toe input per year										
Carbon capture technologies	Pre-Combustion CO_2 capture (IGCC)	HCACS	31	10	10	10	10	10	10	10	10	10	10
	Post-Combustion CO_2 capture (Conventional Coal)	HCCCS	52	25	23	21	20	20	20	20	20	20	20
	Post-Combustion CO_2 capture (GCC)	GCCCS	31	24	13	13	13	13	13	13	13	13	13
			€99/m3d										
	Pre-Combustion CO_2 capture (Hydrogen Production)	H2CAS	68	68	45	45	45	45	45	45	45	45	45

Table A3. Sustainability indicator levels under all technology policies

Technology policy	**Policy cost**	**Indicators**									
		Climate change indicators						**Security of supply indicators**			
	€bn (undiscounted)	Atmospheric CO_2 concentration (2100) (ppmv)	Atmospheric CH_4 concentration (2100) (ppbv)	Atmospheric N_2O concentration (2100) (ppbv)	Temperature change (2100) (K)	Temperature change (constant sulfate) (2100) (K)	Sea-level rise (2100) (cm)	Oil R:P (global) (2060) (years)	Oil R:C (Europe) (2060) (years)	Gas R:P (global) (2060) (years)	Gas R:C (Europe) (2060) (years)
Baseline	0	701.93	2538.5	461.8	3.239	2.726	40.8	32.56	11.15	45.17	33.35
R&D Doubling	425,368	693.34	2531.3	461.8	3.270	2.702	41	34.39	11.74	44.38	31.09
Zero GERD	-425,368	702.79	2537.8	461.8	3.242	2.729	40.8	32.58	11.15	44.96	33.04
Standardised R&D shocks											
HYD	4.48	701.8	2538.4	461.8	3.238	2.726	40.8	32.50	11.15	45.13	33.07
NUC	22.49	701.86	2538.6	461.8	3.239	2.726	40.8	32.52	11.13	45.15	33.01
NNU	6.98	701.98	2538.3	461.8	3.239	2.726	40.8	32.47	11.20	45.14	33.03
HCC	9.70	701.74	2538.5	461.8	3.239	2.726	40.8	32.54	11.13	45.17	33.17
HCCCS	0.007	701.71	2538.3	461.8	3.238	2.726	40.8	32.50	11.13	45.11	33.05
HCA	3.18	701.94	2538.5	461.8	3.239	2.726	40.8	32.57	11.15	45.18	33.36
HCACS	0.003	701.93	2538.5	461.8	3.239	2.726	40.8	32.56	11.15	45.17	33.35
OLC	9.25	701.85	2538.5	461.8	3.239	2.726	40.8	32.52	11.13	45.17	33.59
GCC	12.36	701.94	2538.4	461.8	3.239	2.726	40.8	32.56	11.15	45.16	33.35
GSC	6.05	701.89	2538.1	461.8	3.239	2.726	40.8	32.66	11.13	45.06	33.65
GTR	12.36	701.96	2538.4	461.8	3.239	2.726	40.8	32.54	11.15	45.14	33.28
GCCCS	0.003	701.71	2538.3	461.8	3.238	2.726	40.8	32.50	11.13	45.11	33.05
WND	2.15	701.71	2538.3	461.8	3.238	2.726	40.8	32.50	11.13	45.11	33.05
STH	1.07	701.42	2538.3	461.8	3.240	2.725	40.8	32.47	11.15	45.17	33.68
SPV	9.94	701.76	2538.4	461.8	3.239	2.726	40.8	32.56	11.13	45.16	33.52
BIP	4.46	701.88	2538.4	461.8	3.239	2.726	40.8	32.49	11.22	45.15	33.40
FCMS	7.47	694.61	2531.6	461.8	3.271	2.706	41	33.74	11.04	44.35	31.25
GASH2NE	0.93	701.79	2538.3	461.8	3.239	2.726	40.8	32.57	11.13	45.16	33.64
H2CAS	0.000	701.93	2538.5	461.8	3.239	2.726	40.8	32.56	11.15	45.17	33.35
COALH2NE	0.37	701.96	2538.4	461.8	3.239	2.726	40.8	32.49	11.15	45.12	33.07
BIOH2NE	0.044	701.74	2538.5	461.8	3.239	2.726	40.8	32.54	11.13	45.17	33.17
ICH	0.81	701.93	2538.5	461.8	3.239	2.726	40.8	32.56	11.15	45.17	33.35
ELVT	0.81	701.7	2538.3	461.8	3.238	2.726	40.8	32.51	11.13	45.12	33.05
HYBB	0.81	701.94	2538.6	461.8	3.239	2.726	40.8	32.61	11.13	45.16	33.64
Non-standard R&D shocks											
HCCCS	1.00	701.71	2538.3	461.8	3.238	2.726	40.8	32.50	11.13	45.11	33.05
HCACS	1.00	701.93	2538.5	461.8	3.239	2.726	40.8	32.56	11.15	45.17	33.35
GCCCS	1.00	701.74	2538	461.8	3.238	2.726	40.8	32.53	11.13	45.16	33.64
H2CAS	1.00	701.94	2538.4	461.8	3.239	2.726	40.8	32.62	11.13	45.14	33.65
BIOH2NE	1.00	701.92	2538.6	461.8	3.239	2.726	40.8	32.61	11.13	45.16	33.64
COALH2NE	1.00	701.68	2538.1	461.8	3.238	2.726	40.8	32.64	11.13	45.17	33.65
FCMS	17.47	693.81	2532.2	461.8	3.272	2.704	41	34.14	11.56	44.17	31.17

Standardised D&D shocks

HCA	10	714.25	2543.9	461.8	3.280	2.758	41.3	34.79	11.95	44.77	29.66
GCC	10	718.05	2541.5	461.8	3.104	2.770	40.4	34.96	11.95	44.02	29.73
GTR	10	701.61	2538	461.8	3.238	2.725	40.8	32.60	11.13	45.12	33.66
GFC	10	694.97	2536.7	461.8	3.260	2.704	40.9	33.40	11.12	44.85	33.68
NNU	10	708.14	2540.4	461.8	3.193	2.747	40.7	34.17	12.08	44.88	29.48
BIP	10	717.27	2546	461.8	3.116	2.768	40.4	35.01	12.04	45.45	29.81
STH	10	716.89	2546.1	461.8	3.109	2.767	40.4	34.64	11.96	45.28	29.90
SPV	10	701.35	2538.3	461.8	3.240	2.725	40.8	32.51	11.15	45.16	33.69
WND	10	701.09	2538.2	461.8	3.236	2.723	40.8	32.88	11.15	45.17	33.69
HEF	10	701.98	2538.3	461.8	3.239	2.726	40.8	32.47	11.20	45.13	32.97
GASH2NE	10	701.76	2538.3	461.8	3.238	2.726	40.8	32.50	11.13	45.17	33.70
COALH2NE	10	701.9	2538.2	461.8	3.239	2.726	40.8	32.50	11.22	45.14	33.03
BIOH2NE	10	701.83	2538.1	461.8	3.238	2.726	40.8	32.60	11.15	45.18	33.69
ICH	10	701.86	2538.4	461.8	3.239	2.726	40.8	32.56	11.13	45.14	33.60
IGH	10	702.13	2533.2	461.8	3.230	2.726	40.8	33.74	11.18	44.22	33.65
IAH	10	701.77	2538.4	461.8	3.239	2.726	40.8	32.53	11.13	45.15	33.19
IHH	10	701.77	2538.4	461.8	3.239	2.726	40.8	32.56	11.13	45.17	33.65
PFC	10	701.66	2538.2	461.8	3.238	2.725	40.8	32.58	11.13	45.15	33.65
AFC	10	701.66	2538.2	461.8	3.238	2.725	40.8	32.58	11.13	45.15	33.65
HFC	10	701.89	2538.5	461.8	3.239	2.726	40.8	32.61	11.13	45.16	33.66
HCACS	10	701.01	2538.3	461.8	3.237	2.724	40.8	32.47	11.00	45.14	33.08
HCCCS	10	699.18	2538.6	461.8	3.222	2.717	40.7	32.57	11.13	45.18	33.92
GCCCS	10	698.9	2538.4	461.8	3.230	2.715	40.7	32.52	11.45	44.81	28.72
H2CAS	10	701.65	2538.1	461.8	3.238	2.725	40.8	32.64	11.13	45.17	33.65

Combined R&D FCMS and standardised D&D shocks

FCHCA	17.47	691.09	2526.8	461.8	3.338	2.691	41.7	34.93	11.69	43.83	30.84
FCGCC	17.47	690.49	2522.9	461.8	3.270	2.688	41.2	34.69	11.66	43.02	32.09
FCGTR	17.47	694.61	2529.5	461.8	3.261	2.705	41	34.15	11.75	43.99	31.67
FCGFC	17.47	694.76	2536.5	461.8	3.275	2.704	41	33.33	11.15	44.91	33.69
FCNNU	17.47	683.62	2522	461.8	3.265	2.674	41.1	34.37	11.70	43.78	31.08
FCBIP	17.47	691.6	2530.3	461.8	3.266	2.695	41	34.89	11.27	44.25	30.82
FCSTH	17.47	690.58	2530.5	461.8	3.266	2.692	41	34.56	11.70	44.31	31.02
FCSPV	17.47	693.76	2530.6	461.8	3.271	2.703	41	34.10	11.72	44.16	31.49
FCWND	17.47	693.21	2530.9	461.8	3.268	2.701	41	34.41	11.73	44.21	30.89
FCHEF	17.47	701.76	2538.5	461.8	3.240	2.726	40.8	32.59	11.13	45.24	33.65
FCGASH2NE	17.47	693.86	2530.3	461.8	3.271	2.703	41	34.06	11.75	44.15	31.44
FCCOALH2NE	17.47	694.04	2531.2	461.8	3.272	2.704	41	34.12	11.71	44.29	31.12
FCBIOH2NE	17.47	694.55	2532.2	461.8	3.272	2.706	41	33.87	11.35	44.22	30.86
FCICH	17.47	694.04	2530.9	461.8	3.272	2.704	41	34.18	11.59	44.14	31.01
FCIGH	17.47	694.32	2527.1	461.8	3.257	2.704	41	34.83	11.72	43.61	31.36
FCIAH	17.47	694.14	2531.1	461.8	3.272	2.705	41	33.97	11.70	44.20	31.01
FCIHH	17.47	694.05	2530.6	461.8	3.272	2.704	41	34.13	11.70	44.13	31.05
FCPFC	17.47	701.65	2538.2	461.8	3.238	2.726	40.8	32.59	11.13	45.14	33.65
FCAFC	17.47	701.9	2538.5	461.8	3.241	2.726	40.8	32.52	11.15	45.15	33.40
FCHFC	17.47	701.85	2538.4	461.8	3.239	2.726	40.8	32.58	11.15	45.14	33.47
FCHCACS	17.47	694.01	2531.2	461.8	3.272	2.704	41	33.84	11.29	44.23	31.00
FCHCCCS	17.47	692.59	2531.6	461.8	3.257	2.699	40.9	33.82	11.29	44.23	31.10
FCGCCCS	17.47	691.5	2531.2	461.8	3.237	2.693	40.8	33.94	11.88	43.68	25.78
FCH2CAS	17.47	694.5	2531.1	461.8	3.273	2.706	41	33.88	11.39	44.24	31.06

Table A4. Impact on sustainability indicators of all technology policies

Technology policy	**Impacts**									
	Climate change indicators						**Security of supply indicators**			
	Atmospheric CO_2 concentration (2100) ppm/€bn	Atmospheric CH_4 concentration (2100) ppb/€bn	Atmospheric N_2O concentration (2100) ppb/€bn	Temperature change (2100) K/€bn	Temperature change (constant sulfate) (2100) K/€bn	Sea-level rise (2100) cm/€bn	Oil R:P (global) (2060) years/€bn	Oil R:C (Europe) (2060) years/€bn	Gas R:P (global) (2060) years/€bn	Gas R:C (Europe) (2060) years/€bn
Baseline	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
R&D Doubling	-2.02E-05	-1.69E-05	0	7.29E-08	-5.74E-08	4.70E-07	4.32E-06	1.38E-06	-1.84E-06	-5.31E-06
Zero GERD	-2.02E-06	1.65E-06	0	-7.05E-09	-6.58E-09	0	-5.69E-08	-2.76E-09	4.78E-07	7.26E-07
Standardised R&D shocks										
HYD	-0.029	-0.022	0	-2.23E-04	-1.11E-04	0	-0.012	0.000	-0.009	-0.061
NUC	-0.003	0.004	0	0	-8.89E-06	0	-0.002	-0.001	-0.001	-0.015
NNU	0.007	-0.029	0	0	1.43E-05	0	-0.013	0.007	-0.004	-0.045
HCC	-0.020	0	0	0	-5.15E-05	0	-0.002	-0.002	0.001	-0.018
HCCCS	-29.508	-26.825	0	-0.134	-0.080	0	-7.122	-2.827	-7.578	-40.712
HCA	0.003	0	0	0	3.15E-05	0	0.003	0.000	0.004	0.002
HCACS	0	0	0	0	0	0	0	0	0	0
OLC	-0.009	0	0	0	-2.16E-05	0	-0.004	-0.003	0.001	0.026
GCC	0.001	-0.008	0	0	0	0	0.000	0.000	-0.001	0.000
GSC	-0.007	-0.066	0	0	-6.61E-05	0	0.017	-0.004	-0.017	0.050
GTR	0.002	-0.008	0	0	8.09E-06	0	-0.001	0.000	-0.002	-0.006
GCCCS	-82.622	-75.111	0	-0.376	-0.225	0	-19.942	-7.917	-21.219	-113.995
WND	-0.102	-0.093	0	-4.65E-04	-2.79E-04	0	-0.025	-0.010	-0.026	-0.141
STH	-0.474	-0.186	0	9.30E-04	-1.49E-03	0	-0.083	0.000	-0.001	0.303
SPV	-0.017	-0.010	0	0	-5.03E-05	0	0.000	-0.002	0.000	0.017
BIP	-0.011	-0.022	0	0	-2.24E-05	0	-0.015	0.016	-0.004	0.012
FCMS	-0.980	-0.924	0	4.29E-03	-2.73E-03	2.68E-02	0.158	-0.014	-0.109	-0.282
GASH2NE	-0.150	-0.215	0	0	-0.0004297	0	0.012	-0.026	-0.010	0.310
H2CAS	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
COALH2NE	0.081	-0.269	0	0	2.69E-04	0	-0.168	0.005	-0.131	-0.738
BIOH2NE	-4.338	0	0	0	-1.14E-02	0	-0.361	-0.481	0.162	-4.075
ICH	0	0	0	0	0	0	0	0	0	0
ELVT	-0.284	-0.247	0	-1.24E-03	-7.42E-04	0	-0.054	-0.026	-0.059	-0.375
HYBB	0.012	0.124	0	0	0	0	0.062	-0.031	-0.012	0.362
Non-standard R&D shocks										
HCCCS	-0.220	-0.200	0	-1.00E-03	-6.00E-04	0	-0.053	-0.021	-0.056	-0.304
HCACS	0	0	0	0	0	0	0	0	0	0
GCCCS	-0.190	-0.500	0	-1.00E-03	-7.00E-04	0	-0.026	-0.025	-0.006	0.292
H2CAS	0.010	-0.100	0	0	1E-04	0	0.063	-0.025	-0.027	0.301
BIOH2NE	-0.010	0.100	0	0	-0.0001	0	0.051	-0.025	-0.011	0.293
COALH2NE	-0.250	-0.400	0	-1.00E-03	-8.00E-04	0	0.081	-0.026	0.002	0.298
FCMS	-0.465	-0.361	0	1.89E-03	-1.29E-03	1.14E-02	0.091	0.024	-0.057	-0.125

Note: zeros (0) represent no impact.

Standardised D&D shocks										
HCA	1.232	0.540	0	4.10E-03	3.16E-03	5.00E-02	0.223	0.080	-0.040	-0.369
GCC	1.612	0.300	0	-1.35E-02	4.38E-03	-4.00E-02	0.240	0.079	-0.114	-0.362
GTR	-0.032	-0.050	0	-1.00E-04	-1.10E-04	0	0.004	-0.003	-0.005	0.031
GFC	-0.696	-0.180	0	2.10E-03	-2.19E-03	1.00E-02	0.084	-0.003	-0.032	0.034
NNU	0.621	0.190	0	-4.60E-03	2.06E-03	-1.00E-02	0.161	0.093	-0.029	-0.387
BIP	1.534	0.750	0	-1.23E-02	4.20E-03	-4.00E-02	0.245	0.089	0.028	-0.354
STH	1.496	0.760	0	-1.30E-02	4.09E-03	-4.00E-02	0.208	0.080	0.012	-0.345
SPV	-0.058	-0.020	0	1.00E-04	-1.80E-04	0	-0.005	0.000	-0.001	0.034
WND	-0.084	-0.030	0	-3.00E-04	-3.70E-04	0	0.033	0.000	0.000	0.034
HEF	0.005	-0.020	0	0	1E-05	0	-0.009	0.005	-0.003	-0.038
GASH2NE	-0.017	-0.020	0	-1.00E-04	-5.00E-05	0	-0.005	-0.002	0.000	0.035
COALH2NE	-0.003	-0.030	0	0	-1E-05	0	-0.005	0.006	-0.002	-0.032
BIOH2NE	-0.010	-0.040	0	-1.00E-04	-4.00E-05	0	0.005	0.000	0.002	0.034
ICH	-0.007	-0.010	0	0	-3E-05	0	0.000	-0.002	-0.003	0.025
IGH	0.020	-0.530	0	-9.00E-04	-2.00E-05	0	0.118	0.002	-0.095	0.030
IAH	-0.016	-0.010	0	0	-4E-05	0	-0.003	-0.002	-0.001	-0.016
IHH	-0.016	-0.010	0	0	-4E-05	0	0.000	-0.002	0.000	0.030
PFC	-0.027	-0.030	0	-1.00E-04	-9.00E-05	0	0.003	-0.002	-0.002	0.030
AFC	-0.027	-0.030	0	-1.00E-04	-9.00E-05	0	0.003	-0.002	-0.002	0.030
HFC	-0.004	0.000	0	0	-2E-05	0	0.005	-0.002	-0.001	0.031
HCACS	-0.092	-0.020	0	-2.00E-04	-2.60E-04	0	-0.009	-0.015	-0.002	-0.027
HCCCS	-0.275	0.010	0	-1.70E-03	-9.10E-04	-1.00E-02	0.001	-0.002	0.001	0.058
GCCCS	-0.303	-0.010	0	-9.00E-04	-1.16E-03	-1.00E-02	-0.004	0.029	-0.036	-0.463
H2CAS	-0.028	-0.040	0	-1.00E-04	-9.00E-05	0	0.008	-0.003	0.000	0.030
Combined R&D FCMS and standardised D&D shocks										
FCHCA	-0.621	-0.670	0	5.67E-03	-2.03E-03	5.15E-02	0.136	0.031	-0.076	-0.144
FCGCC	-0.655	-0.893	0	1.77E-03	-2.21E-03	2.29E-02	0.122	0.029	-0.123	-0.072
FCGTR	-0.419	-0.515	0	1.26E-03	-1.20E-03	1.14E-02	0.091	0.034	-0.067	-0.096
FCGFC	-0.410	-0.114	0	2.06E-03	-1.28E-03	1.14E-02	0.044	0.000	-0.015	0.020
FCNNU	-1.048	-0.945	0	1.49E-03	-2.98E-03	1.72E-02	0.104	0.031	-0.079	-0.130
FCBIP	-0.591	-0.469	0	1.55E-03	-1.81E-03	1.14E-02	0.134	0.007	-0.052	-0.145
FCSTH	-0.650	-0.458	0	1.55E-03	-1.98E-03	1.14E-02	0.114	0.031	-0.049	-0.134
FCSPV	-0.468	-0.452	0	1.83E-03	-1.33E-03	1.14E-02	0.088	0.032	-0.058	-0.106
FCWND	-0.499	-0.435	0	1.66E-03	-1.47E-03	1.14E-02	0.106	0.033	-0.055	-0.141
FCHEF	-0.010	0	0	5.72E-05	-2.29E-05	0	0.002	-0.001	0.004	0.017
FCGASH2NE	-0.462	-0.469	0	1.83E-03	-1.31E-03	1.14E-02	0.086	0.034	-0.058	-0.109
FCCOALH2NE	-0.452	-0.418	0	1.89E-03	-1.25E-03	1.14E-02	0.089	0.032	-0.050	-0.127
FCBIOH2NE	-0.423	-0.361	0	1.89E-03	-1.17E-03	1.14E-02	0.075	0.011	-0.054	-0.143
FCICH	-0.452	-0.435	0	1.89E-03	-1.27E-03	1.14E-02	0.093	0.025	-0.059	-0.134
FCIGH	-0.436	-0.653	0	1.03E-03	-1.28E-03	1.14E-02	0.130	0.032	-0.089	-0.114
FCIAH	-0.446	-0.424	0	1.89E-03	-1.25E-03	1.14E-02	0.081	0.031	-0.055	-0.134
FCIHH	-0.451	-0.452	0	1.89E-03	-1.27E-03	1.14E-02	0.090	0.031	-0.059	-0.132
FCPFC	-0.016	-0.017	0	-5.72E-05	-4.58E-05	0	0.002	-0.001	-0.001	0.017
FCAFC	-0.002	0	0	1.14E-04	-1.14E-05	0	-0.002	0.000	-0.001	0.003
FCHFC	-0.005	-0.006	0	0	-1.72E-05	0	0.001	0.000	-0.001	0.007
FCHCACS	-0.453	-0.418	0	1.89E-03	-1.26E-03	1.14E-02	0.073	0.008	-0.054	-0.134
FCHCCCS	-0.535	-0.395	0	1.03E-03	-1.58E-03	5.72E-03	0.072	0.008	-0.053	-0.129
FCGCCCS	-0.597	-0.418	0	-1.14E-04	-1.89E-03	0	0.079	0.042	-0.085	-0.433
FCH2CAS	-0.425	-0.424	0	1.95E-03	-1.19E-03	1.14E-02	0.076	0.014	-0.053	-0.131

3. GMM Results

The GMM model has been applied to examine the impact of energy-related research and development (R&D) activities and demonstration and deployment (D&D) programs for individual technologies on the sustainability indicators of interest in this study. For doing so, we apply the notion of "shocks", i.e., small one-off incremental variations in the cumulative R&D or the cumulative capacity of a given technology at the beginning of the time horizon (the year 2000).

Our analysis follows the notion of "impact" of a given policy instrument. The impact measure of R&D activities or D&D programs is computed as the ratio Delta Indicator/Instrument Cost. "Delta Indicator" is the incremental change in a given indicator relative to the baseline case, i.e., the case without the application of the policy instrument. By convention, positive values of impacts imply an improvement in the respective sustainability indicator and vice versa. "Instrument Cost" is the estimated cost of applying a given policy instrument.

The costs of R&D activities are measured at "face value", i.e., as the respective expenditures that constitute a "shock". As for the costs of D&D programs, according to the procedure agreed upon in SAPIENTIA, we use the average cost at the margin (i.e. for new equipment at the base year) weighted according to the shares of different technologies in new equipment markets. This provides a measure of the "opportunity cost" (difference of an expensive and a "cheap" option) of a given technology. The rationale behind this measure of the costs of a D&D shock is the fact that most technologies will provide energy services or produce energy carriers throughout their life time. Measuring the D&D costs at "face value", i.e. taking into account only the direct investment costs on the D&D program, would not provide an adequate measure of the total cost of the D&D policy instrument, since it neglects the fact that the D&D shock may lead to the installation of capacity that can be used to generate energy or provide energy services. Measured in this way, the "opportunity cost" of a D&D shock is directly comparable to government R&D funding (measured at "face value") which is direct, front ended and non-reimbursable.

R&D shocks have been performed for a representative set of technologies comprising electricity generation, fuel cells (stationary and mobile applications), CO_2 capture and storage, hydrogen production, and passenger cars. A standard shock size of 10 billion Euro over 10 years has been applied to all technologies. The list of technologies and their abbreviations can be found in Table 3-1 . D&D shocks were performed for a subset of these technologies. The reader should bear in mind that, for a given shock, complex interactions take place within the model, due, among others, to the presence of technology spillovers. Thus, other technologies and energy sectors could be affected by a particular shock.

Table 3-1 Description of technologies for which R&D shocks are performed in this study.

Abbreviation	Description
NUC	Conventional Nuclear power (Generation III+)
PFC	Supercritical pulverized coal
IGC	Integrated Gasification Combined Cycle
GGC	Gas turbine combined cycle (includes gas turbine open cycle)
WND	Wind turbine
SPP	Solar thermal power plant
DPV	Solar photovoltaics
BGT	Biomass gasification power plant
FC	Fuel cells (stationary and mobile)
PSSC	Post-combustion CO_2 capture for supercritical pulverized coal
CGSC	Pre-combustion CO_2 capture for Integrated Gasification Combined Cycle
GGSC	Post-combustion CO_2 capture for gas turbine combined cycle
GSSC	Pre-combustion CO_2 capture for gas steam reforming hydrogen production
GSR	Hydrogen from gas steam reforming
WEG	Hydrogen from water electrolysis
CPO	Hydrogen from coal partial oxidation
BPY	Hydrogen from biomass pyrolysis
HYBV	Hybrid passenger car (includes electric passenger cars as well)
THYV	Hydrogen internal combustion engine passenger car

3.1. The Impact of R&D Shocks

We first examine the impact of R&D shocks on the sustainability indicators under examination here. Figure 3-1 presents the impact of R&D shocks on cumulative CO_2 emissions for the period 2000-2050. As can be seen, several of the technologies considered here have a positive impact on this indicator. The largest impact is achieved by nuclear power plants (NUC), followed by hybrid-electric vehicles and wind turbines. The most noticeable negative impacts are produced by R&D shocks on coal-based IGCC power plants, CO_2 capture for gas combined-cycle turbines (due to the substantial energy penalty of the post-combustion CO_2 capture process) and coal-based hydrogen production. The small positive impact of the supercritical pulverized coal power plant is due to the fact that it displaces less efficient conventional coal-fired electricity generation but the R&D shock does not lead to a sizeable increase of coal-based electricity production. In contrast, the R&D shock on coal-based IGCC does increase substantially the amount of total coal-based electricity production leading to a negative impact on cumulative CO_2 emissions. Under the assumptions and the CO_2 tax levels assumed here, the impact of R&D shocks for several technologies is negligible.

Figure 3-1 Impact of R&D shocks on cumulative CO_2 emissions for the period 2000-2050. For the meaning of technology abbreviations see Table 3-1 above. Positive values indicate a positive impact, in this case a reduction of the cumulative CO_2 emissions.

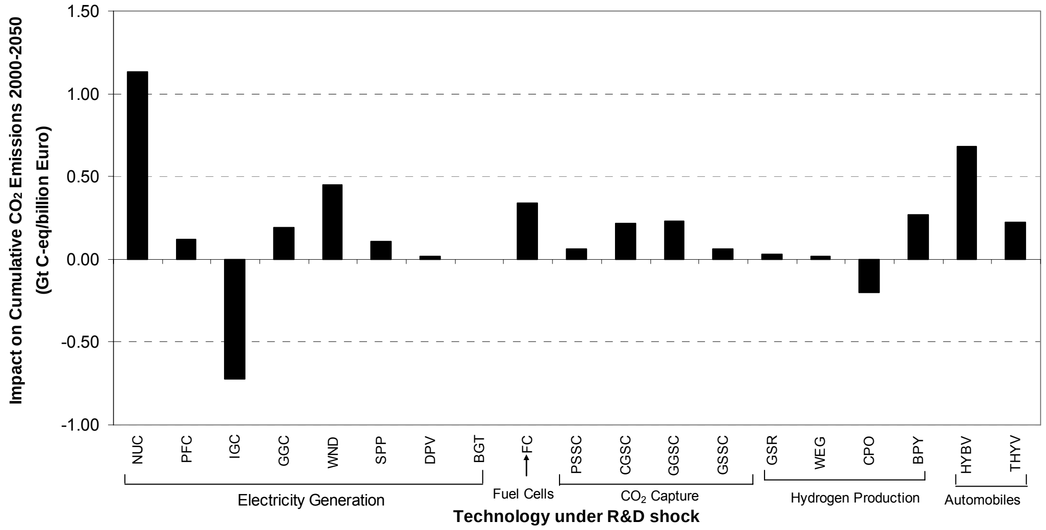


Figure 3-2 depicts the impact of R&D shocks on cumulative CH_4 emissions for the period 2000-2050. The most noticeable positive impact is that of nuclear power plants, which displace coal-based and gas-based electricity generation thus reducing methane emissions. The most sizeable negative impacts are those of R&D shocks on gas combined-cycle turbines and CO_2 capture in gas combined-cycle turbines, which lead to an increase in gas consumption and associated methane emissions in our scenario. Other technologies with negative impact are wind turbines and biomass-based gasification for electricity production. Shocks in these two technologies displace gas-based electricity generation. This natural gas is redirected to the transportation sector, resulting in a net increase of gas consumption as compared to the baseline scenario.

Figure 3-2: Impact of R&D shocks on cumulative CH_4 emissions for the period 2000-2050. For the meaning of technology abbreviations see Table 3-1 above. Positive values indicate a positive impact, in this case a reduction of the cumulative CH_4 emissions.

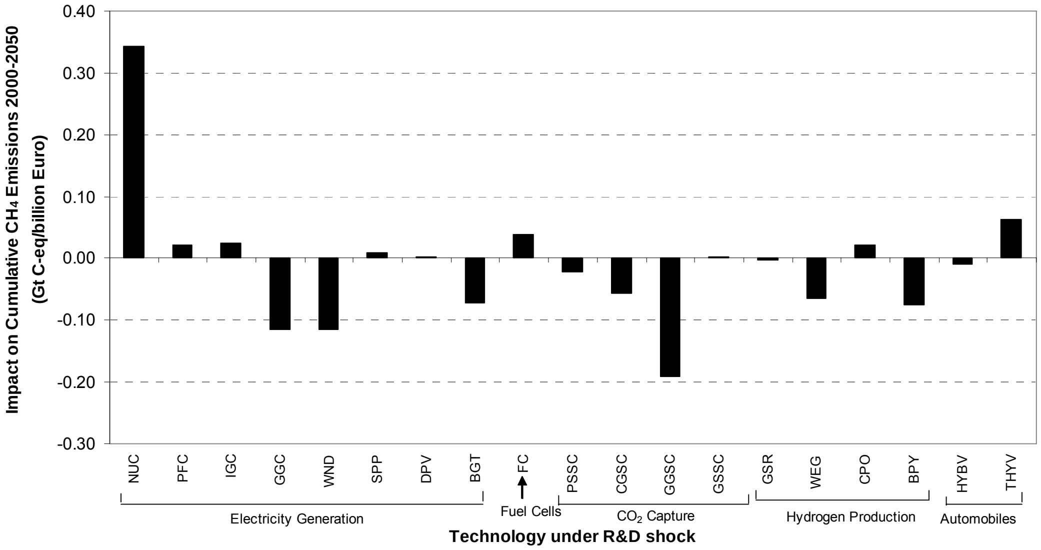


Figure 3-3 presents the impact of R&D shocks on the global temperature commitment for the year 2065. Global temperature change is measured using the year 1990 as reference. Due to the inertia in the climate system, the R&D shocks promoting the introduction of individual technologies have a lesser impact on global temperature change than they have on cumulative GHG emissions. Positive impacts can be observed for nuclear power plants, hybrid-electric cars, hydrogen-powered ICE vehicles and supercritical pulverized coal power plants (in the latter for the reasons explained above). Negative impacts are observed for coal-based IGCC and coal-based hydrogen production.

Figure 3-3 Impact of R&D shocks on the global temperature commitment for 2065. For the meaning of technology abbreviations see Table 3-1 above. Positive values indicate a positive impact, in this case a reduction of the global temperature commitment.

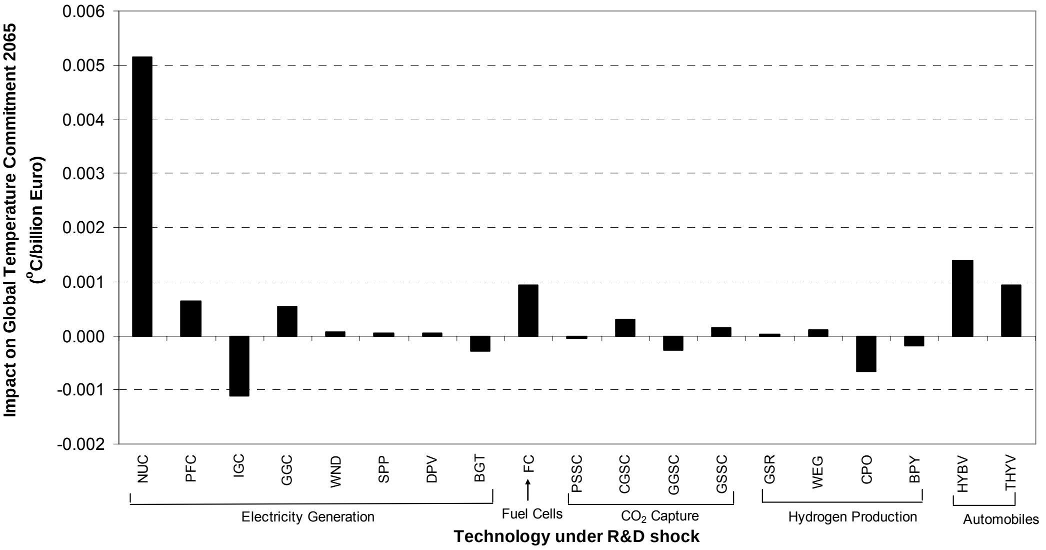
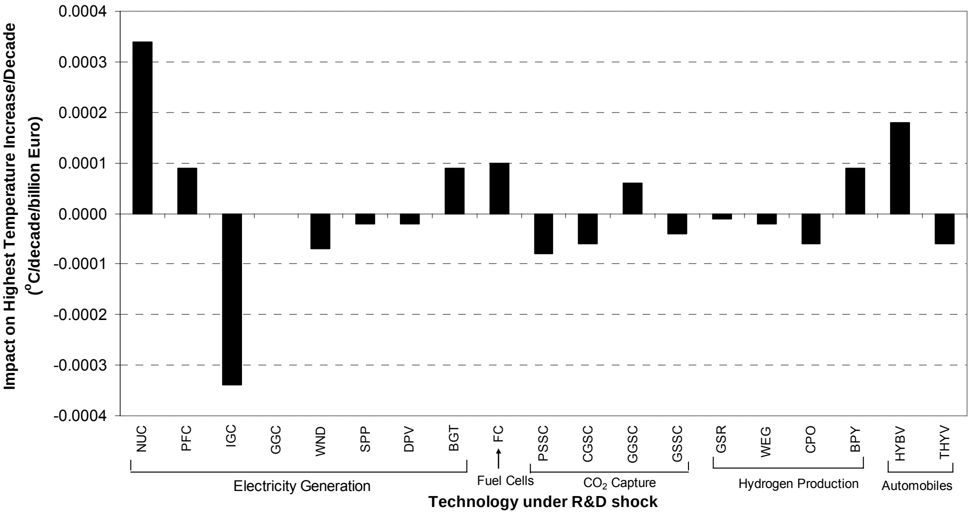


Figure 3-4 presents the impact of R&D shocks on the highest temperature increase per decade for the period 2000-2050. Positive impacts can be observed for conventional nuclear power, hybrid vehicles, hydrogen and electricity production from biomass and fuel cells. The most noticeable negative impact is that of coal-based IGCC power plants. The reader should notice, however, that impacts measured on this indicator for this set of shocks were very small and are close to the range of model precision.

Figure 3-4 Impact of R&D shocks on the highest temperature increase over a decade for the period 2000-2050. For the meaning of technology abbreviations see Table 3-1 above. Positive values indicate a positive impact, in this case a reduction of the highest temperature increase per decade.



The following figure shows the impact of R&D shocks on the oil resources/production ratio for the year 2050. The R&D shock on CO_2 capture in gas combined-cycle turbines, which leads to an increase in gas consumption in the electricity sector, reduces the availability of natural gas in the transportation sector. Consequently, CNG hybrid-electric vehicles are replaced by oil-based conventional ICE vehicles leading to an increase in oil consumption and, thus, a reduction in the oil Ru/P ratio. As for the effect of hybrid-electric vehicles and hydrogen-powered ICE cars, their uptake due to the R&D shock effectively reduces the amount of oil-products-based ICE vehicles and reduces the consumption of oil in the passenger-car sector and, therefore, total primary oil consumption is reduced.

Figure 3-5: Impact of R&D shocks on oil resources/production ratio for the year 2050. For the meaning of technology abbreviations see Table 3-1 above. Positive values indicate a positive impact, in this case an increase of oil resources/production ratio.

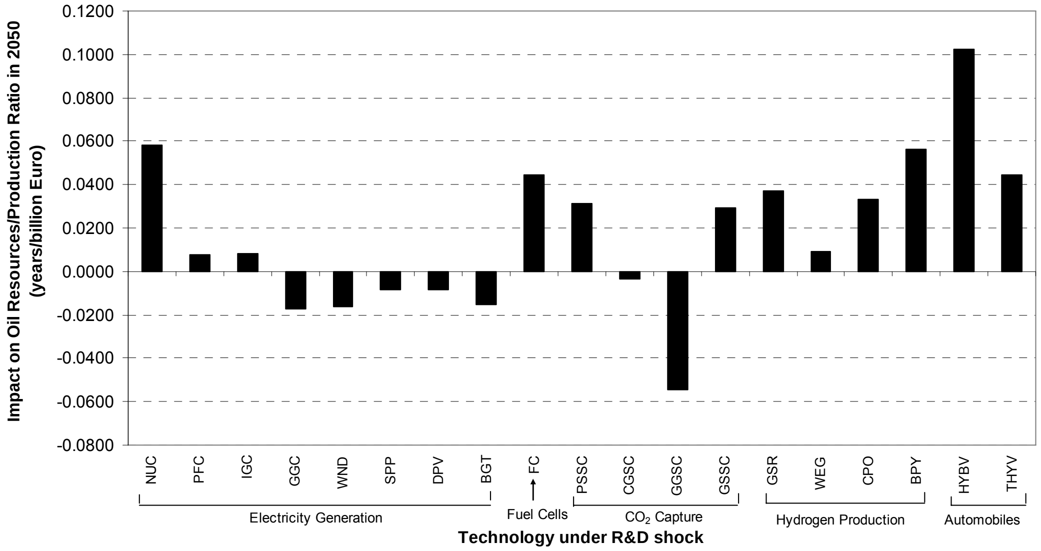
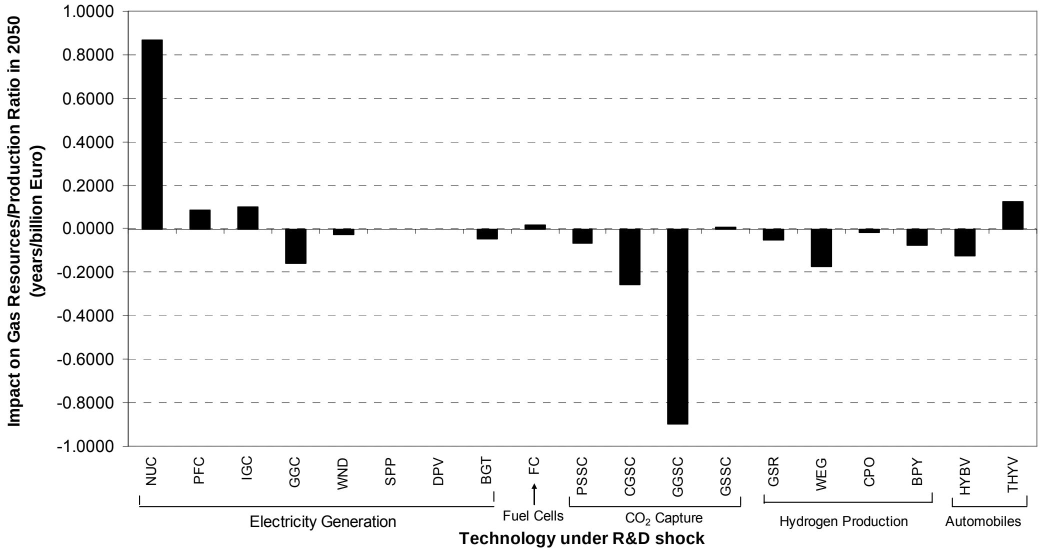


Figure 3-6 shows the impact of R&D shocks on the gas resources/production ratio for the year 2050. The most significant positive impact is produced by the nuclear power plant, which displaces coal and gas-based power plants in the electricity sector. The most significant negative impact is produced by the introduction of CO_2 capture in combined-cycle gas turbines. Its diffusion increases the consumption of natural gas in the electricity sector and, therefore, brings an increase on the total primary-energy consumption of natural gas. This substantially reduces the resources/production ratio of natural gas in the year 2050.

Figure 3-6: Impact of R&D shocks on gas resources/production ratio for the year 2050. For the meaning of technology abbreviations see Table 3-1 above. Positive values indicate a positive impact, in this case an increase of gas resources/production ratio.



The next figure presents the impact of R&D shocks on the fraction of oil production originating in the LAFM region in the year 2050. The LAFM region comprises Latin America, Africa and the Middle East. In the case of this indicator, the impact of CO_2 capture in combined-cycle gas turbines, hybrid-electric vehicles and hydrogen-based ICE is negative. Although these technologies reduce the oil consumption, this reduction means that the more expensive resource categories are not used. Thus, a larger fraction of the remaining oil is produced in the LAFM region, where cheaper oil is available.

Figure 3-7: Impact of R&D shocks on the fraction of oil production from the LAFM region in the year 2050. The LAFM region comprises Latin America, Africa and the Middle East. For the meaning of technology abbreviations see Table 3-1 above. Positive values indicate a positive impact, in this case a reduction of the fraction of oil produced in the LAFM region.

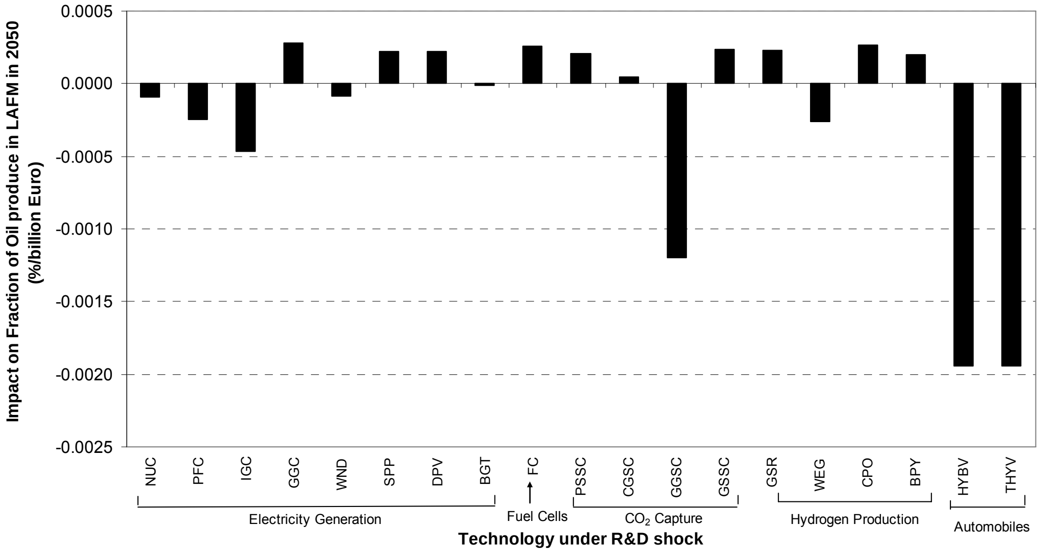
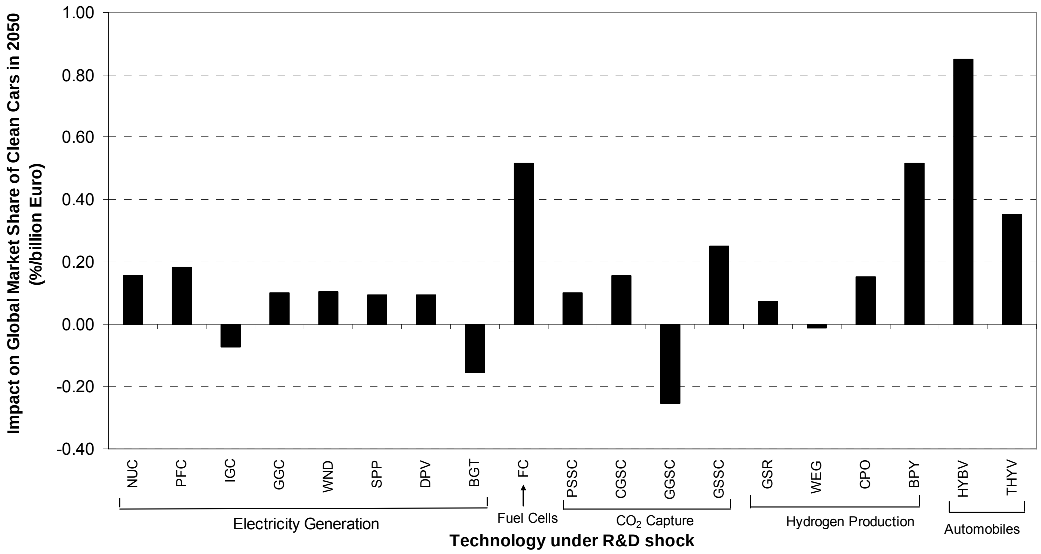


Figure 3-8 portrays the impact of the set of R&D shocks under examination here on the global market share of clean passenger cars (represented here by the summation of the market shares of hybrid vehicles, electric vehicles, hydrogen ICE vehicles and fuel-cell vehicles in the passenger car sector) for the year 2050. The largest positive impact is achieved by the hybrid-electric passenger car, followed by fuel cells[32], biomass-based hydrogen production and the hydrogen-based ICE vehicle. The introduction of CO_2 capture in combined-cycle gas turbines increases the consumption of natural gas in the electricity sector but reduces the availability of gas for the passenger car sector, leading to a reduction in the global market share of gas-powered hybrid and fuel-cell vehicles.

Figure 3-8: Impact of R&D shocks on the global market share of clean passenger cars in the year 2050. For the meaning of technology abbreviations see Table 3-1 above. Positive values indicate a positive impact, in this case an increase of the global market share of clean passenger cars.



Although this analysis helps to identify promising technological options, in general terms, however, the individual R&D shocks had relatively small impacts on the sustainability indicators under analysis. Partially, this is related to the specific structure of the GMM model and the approach used here to capture the role of R&D. However, besides these aspects, the fact that most of the R&D shocks target individual technologies plays also a role. Regarding the latter, our results point out the need for a well-targeted support to promising clusters of related, mutually-reinforcing technologies, where learning spillovers could take place, rather than to individual technologies.

3.2. The Impact of D&D Shocks

In this section, we briefly discuss the impacts of D&D shocks in a selected subset of technologies on the sustainability indicators under analysis here. We have chosen five (5) electricity generation technologies for this exercise, namely conventional nuclear plants, coal-based IGCC, wind turbines, solar photovoltaics and biomass-based gasification technologies. A standard size equivalent in value to the R&D shocks conducted previously has been used for the D&D shocks. As explained above the costs of the D&D shock are estimated applying the concept of opportunity cost described in Kouvaritakis and Panos (2005b), using the natural gas combined-cycle turbine (GGC) as the reference technology. That is, the D&D cost is computed in Euro/kW as follows:

$$D\&D\_\cos t_{te} = 8760 * af_{te} * \left(GenCo_{te} - GenCo_{ggc}\right) * \int_0^{lifetime_{te}} e^{-rt} dt \tag{1}$$

---

[32] Within SAPIENTIA, joint learning between stationary and mobile fuel cells is assumed.

Where:

af_{te}: Availability factor of technology te

$GenCo_{te}$: Generation cost of technology te

$lifetime_{te}$: Lifetime of technology te

r: Discount rate

Figure 3-9 presents the impact of D&D shocks on cumulative CO_2 and CH_4 emissions for the period 2000-2050. The impact of all the technologies in this subset on CO_2 and CH_4 emissions is positive. Esentially, these electricity generation technologies displace coal-based electricity generation, which leads to a reduction in CO_2 emissions. Coal-based IGCC exhibits a positive impact because it replaces conventional coal-based generation but, in contrast to the case of the R&D shock on this technology, the D&D shock does not lead to an increased deployment of coal-based electricity generation. As for the impact on CH_4 emissions, the uptake of these technologies leads to a displacement of gas-based electricity generation (mainly combined-cycle turbines). Part of the natural gas that is freed is redirected to other sectors, transportation among them. However, the total consumption of natural gas is noticeably reduced in the D&D-shock cases, thus leading to a reduction in CH_4 emissions from this source. In addition, there are less CH_4 emissions from coal production in the D&D-shock cases.

Figure 3-9: Impact of D&D shocks on cumulative CO_2 and CH_4 emissions for the period 2000-2050. For the meaning of technology abbreviations see Table 3-1 above. Positive values indicate a positive impact, in this case a reduction of the cumulative CO_2 emissions.

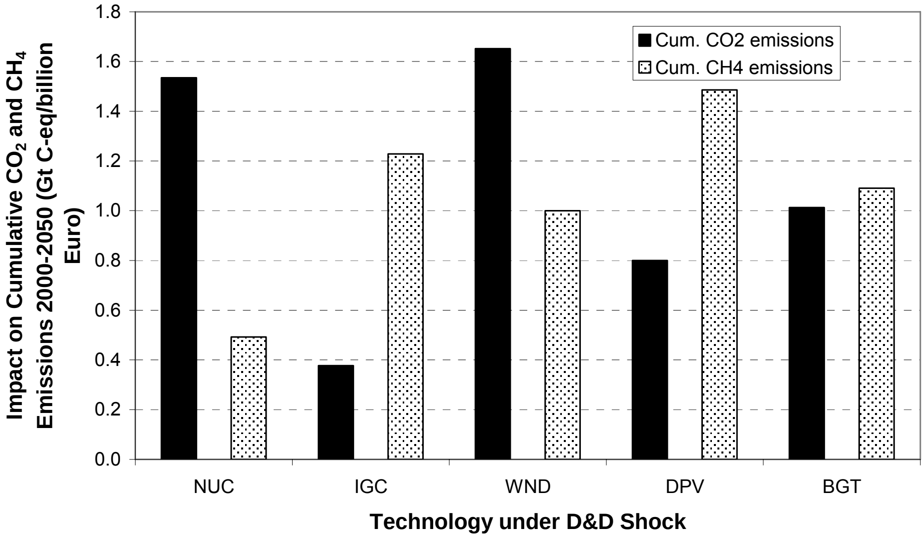


Figure 3-10 depicts the impact of D&D shocks on the global temperature commitment for 2065 and the highest temperature increase per decade for the period 2000-2050. Impacts on both indicators are positive for this subset of electricity generation technologies. However, please notice that the impacts on highest temperature increase per decade are very small.

Figure 3-10 Impact of D&D shocks on the global temperature commitment for 2065 and the highest temperature increase for the period 2000-2050. For the meaning of technology abbreviations see Table 3-1 above. Positive values indicate a positive impact, in this case a reduction of the global temperature commitment.

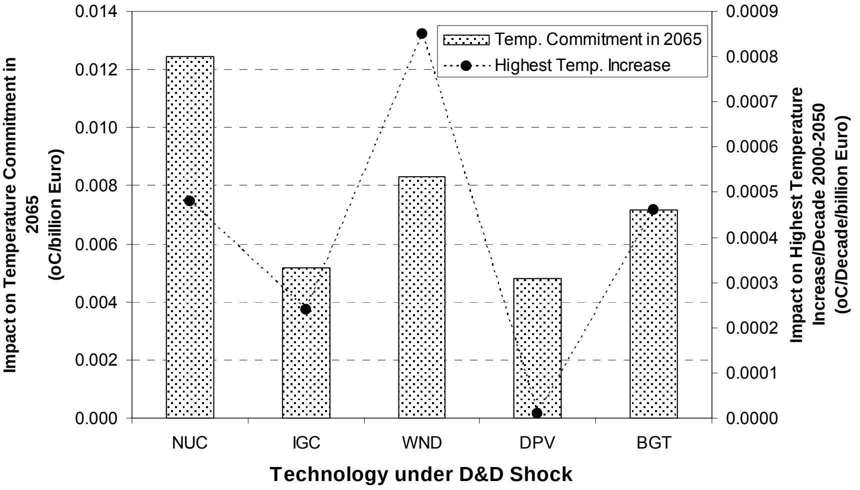


Figure 3-11 shows the impact of D&D shocks on oil and gas resources/production ratios for the year 2050. Generally, the impact of D&D shocks on these electricity generation technologies is positive for the gas Ru/P ratio because they displace gas-based generation. Impacts on the oil Ru/P were small.

Figure 3-11: Impact of D&D shocks on oil and gas resources/production ratios for the year 2050. For the meaning of technology abbreviations see Table 3-1 above. Positive values indicate a positive impact, in this case an increase of the resources/production ratio.

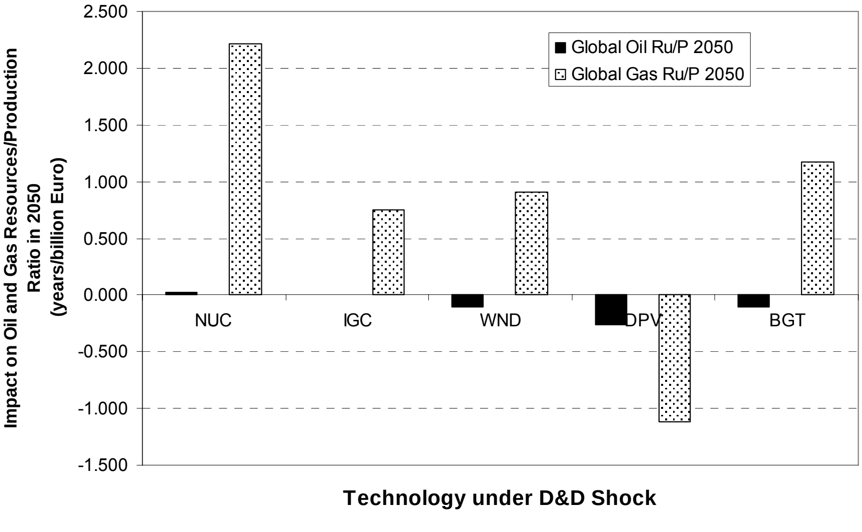


Figure 3-12 illustrates the impact of D&D shocks on the fraction of oil production from the LAFM region in the year 2050. The LAFM region comprises Latin America, Africa and the Middle East. Impacts of D&D shocks on this indicator were essentially negligible.

Figure 3-12: Impact of D&D shocks on the fraction of oil production from the LAFM region in the year 2050. The LAFM region comprises Latin America, Africa and the Middle East. For the meaning of technology abbreviations see Table 3-1 above. Positive values indicate a positive impact, in this case a reduction of the fraction of oil produced in the LAFM region.

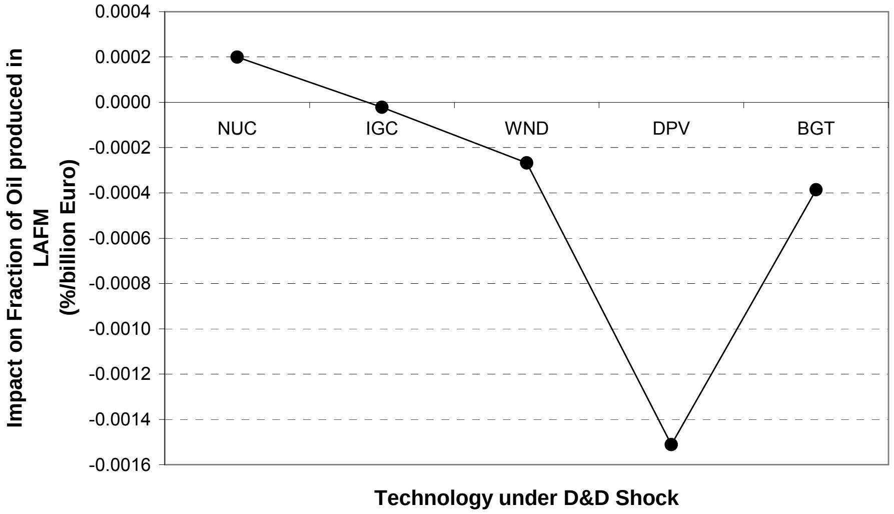
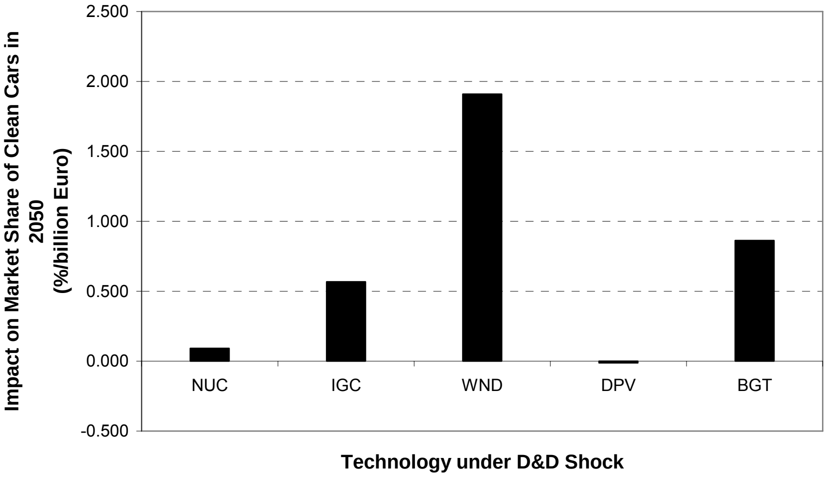


Figure 3-13 presents the impact of D&D shocks on the global market share of clean passenger cars in the year 2050. Most of the technologies in this subset exhibit a significant positive impact on this indicator. This is due to the fact that the electricity generation from these technologies displaces gas-based electricity production. A significant fraction of this freed gas is redirected to the passenger car sector where it is mainly used in gas-powered hybrid-electric cars. The small negative impact due to the D&D shock on solar photovoltaics can be considered negligible (and assumed to be zero).

Figure 3-13 Impact of D&D shocks on the global market share of clean passenger cars in the year 2050. For the meaning of technology abbreviations see Table 3-1 above. Positive values indicate a positive impact, in this case an increase of the global market share of clean passenger cars.



Generally, when comparing the magnitude of the impacts due to R&D and D&D shocks of equivalent size for a given technology, impacts tend to be higher for the D&D shock in our modeling framework, although this depends on the relative values of the learning-by-doing and learning-by-searching elasticities. This is partially due to the fact that the learning-by-doing mechanism is entirely endogenized in the GMM model while we are relying on an exogenous approximation for the learning-by-searching mechanism. Consequently, while the R&D shock leads to a one-time downwards shifting of the corresponding learning curve, the D&D shock directly setting in motion the mechanism of capacity (experience) accumulation appears to be more effective. However, the main explanation for the difference impacts lies in the way the costs of R&D and D&D shocks are estimated. As mentioned above, D&D shocks are evaluated using a notion of "opportunity cost" that reflects the fact that the government does not pay fully for the costs of demonstration and deployment programs, while government R&D funding is direct and non-reimbursable.

4. MARKAL Results

ECN treats the impact of energy R&D indirectly in the MARKAL model, through estimates of the impact on the progress ratio of the 1FLC from externally applied R&D expenditure shocks. This approach has been formulated and first tested in the ECN contribution to the SAPIENT project. The basic assumptions behind the approach are:

2. An additional R&D budget (an '*R&D shock*') will lead to an increase in the so-called *R&D intensity* of the technology. R&D intensity is defined as the relationship between the R&D expenditures over a period and the turnover or sales of that technology during the same period:
   R&D intensity = (amount of R&D)/(amount of R&D + turnover)
3. The higher the R&D intensity, the better the progress ratio.
4. This relationship between a change in R&D-intensity and the change in progress ratio is the same for each technology.
5. R&D budget for each technology is applied with the same level of efficiency.
6. The progress ratio will not change after the period of additional R&D shock.

The approach is then as follows:

1. The MARKAL model uses the 'overall' progress ratio that includes all factors of learning, including effects of R&D.
2. An additional R&D budget (an 'R&D shock') will lead to an increase in the R&D intensity of the technology.
3. An increased R&D intensity will lead to a lower (= better) progress ratio.
4. This updated progress ratio is used in the MARKAL model to study the overall impact of R&D.

The quantitative relationship between R&D intensity and the change in progress ratio has been based on available statistics/data for a couple of technologies in the course of the TEEM and SAPIENT project. It was concluded that the R&D-intensity elasticity for learning is a 0.29% lower (=better) progress ratio for each additional R&D-intensity %point.

Based on the relationships outlined above, the procedure to analyse the impact of R&D is as follows:

1. Estimate the current progress ratio (PR_0) of technology T_i without extra R&D over a given historical period P_i
2. Estimate the R&D-intensity of this technology T_i over the same historical period P_i
3. Calculate what would be the amount of R&D to be spent in a reference scenario, assuming that the R&D-intensity stays constant over time.
4. Estimate an extra R&D budget that is at least the amount calculated in 3.
5. Calculate what the extra R&D budget of x billion Euro means for the change in R&D-intensity (ΔRD_I).
6. Multiply ΔRD_I by 0.29: This gives the change in PR, ΔPR.
7. Add ΔPR to PR_0, resulting in PR_{new}, the new PR, enhanced by additional R&D.

The cumulative sales and cumulative R&D are derived from time series data established by IEPE for the POLES model technologies and from ECN (Part B-III). A reclassification of these data to the MARKAL learning components has been done, like in the SAPIENT project and using a similar matrix as the cluster matrix.

However, in MARKAL there are a couple of components on which POLES and IEPE has no data provided. For these components an own estimate of the R&D intensity has been made, since no data sources for sales or R&D exist. Annex 2 gives the overview of the data used in the determination of the improved PR due to R&D shocks. In general it can be concluded that very mature technologies (e.g. engines, hydro, boiler) have a low R&D intensity (<10%), technologies on the edge of break through or in full market deployment (e.g. steam turbine, gas turbine, wind turbine) have a R&D intensity between 10 and 50% and speculative, immature or new development technologies (e.g. solar PV, fuel cells, electrolysis) have a high intensity (50-100%).

The purpose of applying a R&D shock is to increase the R&D intensity which in its turn will improve the progress ratio of the technology. The CO_2POL1 and CO_2POLH cases are rerun with each time a single technology receiving its improved progress ratio. No other adjustments to the technology parameters or database are made. For instance, for technologies that have reached their assumed maximum potential already in one of the CO_2 tax cases, that potential level is kept unchanged. This could hamper wider deployment of certain technologies when the R&D shock is applied, but no literature exists on the impact of R&D on increased market potential. Furthermore, to re-estimate potentials giving improved learning and possible enhanced deployment go beyond the scope of this study because this would need a complete re-definition of the database storyline and assumptions.

4.1. R&D shock results

In first instance, the results are checked to look for considerable different deployments of this technology. When there is a substantial difference, changes in the other results parameters (primary energy, CO_2 emissions,…) will also be analysed. As already stated in the report on the MARKAL contribution to the SAPIENT project, R&D shocks prove to have only little effect on the technology deployment speed and level, even if due to the lower progress ratio, specific investment costs are considerable lower for a similar cumulative capacity.

The following table gives a quick overview of the R&D shock application on three major indicators used for a quick scan of the results. Notice that these are not the indicators mentioned earlier in this report, they are only used to select those learning components for which a R&D shock prove to generate noticeable differences in the results.

Table 4-1: **Result differences between the without and with R&D shock case for overall indicators**

Case Compared to CO2POL1	Difference in CO_2 emissions 1990-2050 %	Difference in (undiscounted) total system costs 1990-2050 %	Difference in welfare loss 1990-2050 %
PRCC1COAL$^+$	-0.1	0.1	1.2
PRCC2COAL*	-0.2	0	1.0
PRCCB*	0.1	-0.1	-3.1
PRCCGAS*	0	0	-2.2
PRCO2INJ*	0	0	-0.1
PRCPO$^+$	0	0	0
PRFC$^+$	0	0	0
PRGF*	0.1	0	-1.1
PRGT*	-0.2	0	-2.4
PRGSR$^+$	0	0	-0.5
PRHP$^+$	0	0	-0.2
PRRESCB$^+$	0	0	-0.1
PRSOLPV$^+$	0	0	-0.1
PRWIND$^+$	-0.2	0.1	1.3
PRSEH$^+$	0	0	-0.2
PRETG$^+$	0.1	0	-2.0
PRBOIL$^+$	0.1	0	-0.4
* : detailed analysis + : more qualitative analysis			

Note: negative numbers for difference in welfare loss, mean actually a net gain.

From the table above, it is clear that singular R&D shocks on technologies have a small to negligible impact on the model outcome. Especially when looking at overall result parameters like CO_2 emissions and total system costs, the differences are small and partly attributable to model dynamics and not only to the induced R&D shock input. Furthermore, the model is run using elastic demands, so demand levels can change as well, resulting in another energy system than the original.

The welfare loss (difference in consumer and producers' surplus) changes the most; this is not surprising because the technology costs become cheaper due to the lower progress ratio. This is even the case when the invested capacity does not change compared to the CO_2POL1 case (e.g. PRWIND case). Similar capacities at reduced costs lead to less expenditures by the producers and hence a lower welfare loss.

The more mature and already favourable technologies (boilers, etcetera, but also gas turbines and gasifiers) can increase their deployment caused by the additional R&D expenditures and make a difference in the results. More promising technologies like solar PV and fuel cells do not profit from this R&D shock and the results remain unchanged.

The reasons for this non-break through are the following:

- the introduction of the CO_2 tax already forces the model to choose for specific options (lock in); by doing so a number of (zero-or less emission) technologies do not achieve a market penetration (lock out).
- the storylines beyond the future technology deployment and behaviour are matched to the original background assumptions of the model; this means that there are a multitude of assumptions, both promoting or restrictive, concerning fuel share use, useful energy shares (e.g. buildings) and technologies (investment constraint, deployment potentials). They play a role in the model's decision for future investments and deployment, they help to shape the solution and to avoid a too dynamic behaviour (flip-flop effects) of the model. This behaviour would be correct from a pure optimisation formulation point of view, but not if one wants to explore possible future energy systems and scenarios.
- R&D shocks can improve the learning curve for technologies, but are not a guarantee for successful market deployment. Certainly for a complex model like MARKAL with a lot of competitors, alternatives and substitution possibilities all the internal interactions and links prohibit radical changes when only a single parameter is changed per case.
- more policy interventions are necessary to introduce specific technologies like solar PV and fuel cells than only a R&D shock, this can be done by subsidising end user to open the market or by setting targets for market deployment.

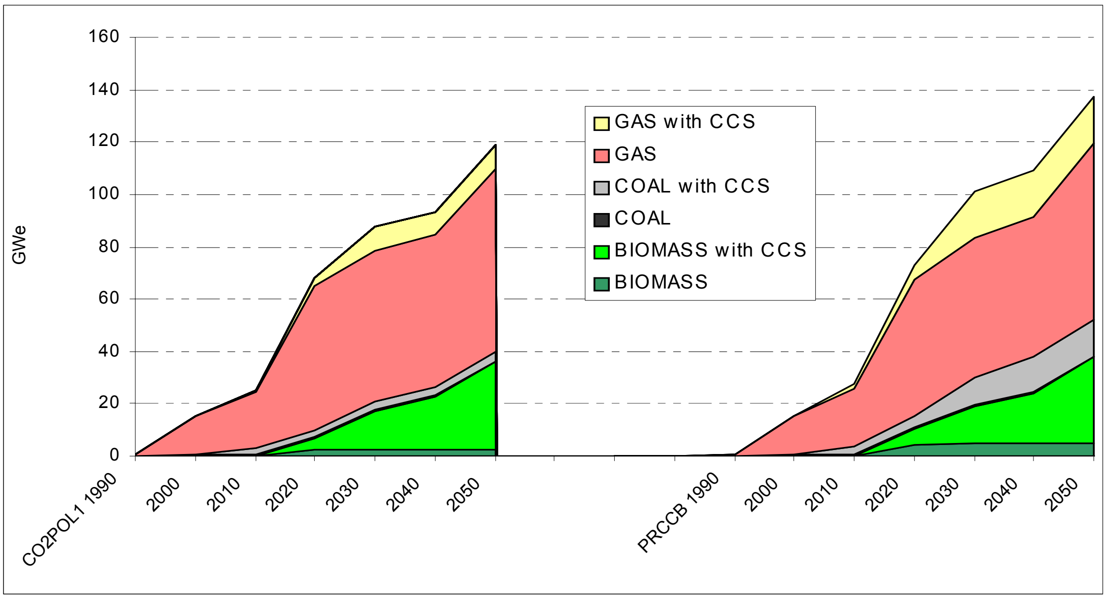
Nevertheless, it is not because overall results do not change visibly, that no effects can be found. These effects are there, but on a much deeper level in the model than the indicators. The effects play on technology level and intra-sectoral deployment. On these levels changes can be seen and explained. Unfortunately, all the technologies where these effects occur, are found mainly in the power sector: gasifiers, gas turbines, wind turbines, CO_2 capture from input coal flow. Their results are discussed in detail in the next paragraphs.

4.1.1. Combined cycle recovery boiler

This component situates itself after the gas turbine and before the steam turbine in a combined cycle power unit. This combined cycle unit can be fuelled by natural gas directly, but also by gasified other fuels like coal or biomass. If the capacity development of this component is influenced by the applied R&D shock also components directly linked (gas turbine, steam turbine) to this one experience an impact. What is more, possibly also components upstream (gasifier) and downstream (CO_2 capture and injection) are influenced.

The R&D shock increases the deployment of combined cycles with about 15% by 2050 to a total level of 138 GWe (cumulative capacity). The kind of units, with or without CCS, also changes, but not proportionally to the total increase, the input fuel mix changes as well. The following Figure 19 illustrates both effects, showing the standard CO_2-restricted case in the left panel, and the effects of the R&D-shock in the right panel. There is slightly more biomass without CCS appearing, but the total capacity biomass fuelled remains constant; there is almost triple as much coal with CCS and a double amount of gas with CCS. Gas and coal without CCS do not change much.

***Figure 4-1* Cumulative capacity for combined cycle recovery boilers without (CO_2POL1 case) and with (PRCCB case) R&D shock**



Other effects from the increased use of combined cycle boilers are indeed to be found both upstream (more gasification of coal) and downstream with more CCS from the power sector. This on its turn has an effect on the electricity production: gas with CCS based production increases and substitutes a small amount of regular gas fuelled production and also of biomass with CCS fuelled production. The technologies involved with coal fuelled production change as well, since the combined cycle option has now become more advantageous, the post combustion capture almost disappears completely in favour of pre-combustion capture in a combined cycle. The total electricity production is hardly increased with a few tenths TWh.

The earlier (2030-2030) deployment of gas CCS technologies makes that the ECBM reservoir is filled earlier, triggering storage in EOR and even in deep ECBM in 2050. The latter are used as the exhaustion of the storage capacity of the ECBM in combination with the existing and continuing flow from capture technologies in the power sector require alternative storage facilities. Moreover, there is no substitution in CO_2 capture with industry or fuel conversion, so the amount to store increases due to the increased capacity of carbon capture technologies.

Another side effect is that the increase in CCS with the preferential storage in ECBM generates more methane into the energy supply, this methane substitutes partly the additional import of gas needed for the additional gas fuelled power plants in 2020 and 2030. Afterwards, there is more need for gas, so the import increases. Also the coal supply changes somewhat; domestic coal is substituted by import in the later periods. All in all imports increase by the end of the time horizon, making the situation of the supply security less favourable. Nonetheless, the diversity index hardly changes; changes in one fuel are compensated by an opposite change in another.

This change in supply has an impact on the indicators related to the energy supply and security. The next table gives the changes between this case and CO_2POL1, a positive value means an improvement.

***Table 4-2:* Changes in the energy supply indicators, PRCCB case versus CO_2POL1 case**

	1990	2000	2010	2020	2030	2040	2050
Import independency	0.0%	0.0%	-0.1%	0.1%	0.0%	-0.9%	-0.7%
Shannon index 1	0.0%	0.0%	0.0%	0.0%	-0.2%	-0.2%	0.1%
Shannon index 2	0.0%	0.0%	-0.1%	-0.1%	-0.2%	-1.0%	-0.7%
Shannon index 3	0.0%	0.0%	-0.1%	-0.1%	-0.2%	-1.1%	-0.8%

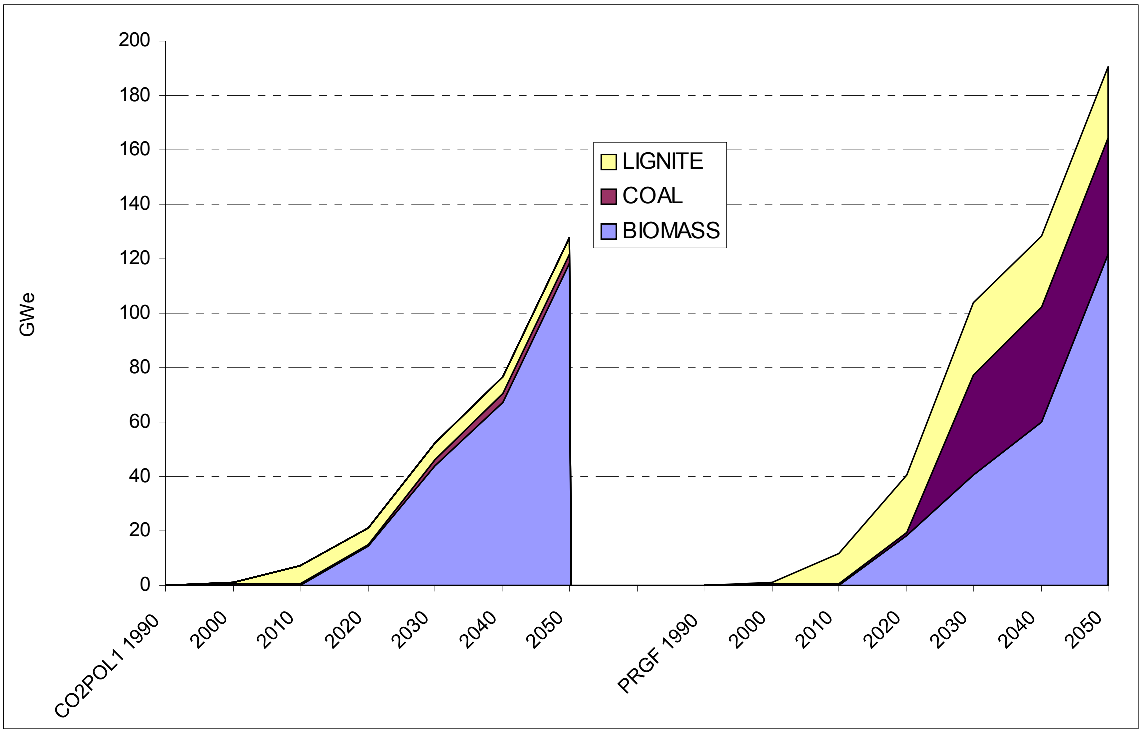
The increase in gas imports causes the indexes to drop in 2040-2050.

4.1.2. Gasifiers

The R&D shock causes a couple of changes in the deployment of gasifiers: not only the absolute level of the cumulative capacity built up over 1990-2050 increases from 128 to 191 GWe, but also the deployment changes over different applications in the power sector.

The following Figure 20 illustrates this change: compared to the CO_2POL1 case, gasifiers for lignite are introduce earlier (2010), lignite being the cheapest fuel available even in presence of a modest CO_2 tax. After 2020, coal takes over (higher efficiency than a comparable lignite integrated gasification plant). The final deployment of biomass gasification is rather similar to the case without R&D shock although up to 2040 it is lower. All power plants using gasifiers, including the biomass ones, are also equipped with CO_2 capture facilities.

***Figure 4-2:* Cumulative capacity for gasifiers without (CO_2POL1 case) and with (PRGF case) R&D shock**



The shock in R&D expenditures for gasifiers, and the resulting change in capacity deployment, leads to changes in electricity production. Coal and lignite substitute almost all gas fired production with CCS (~ 100 TWh) and some biomass production (~ 50 TWh in 2030-2040). The substitution causes a small (~ 1%) increase in total electricity production.

The decreased dependency on gas induces improved security of supply, as the need for imported gas diminishes. This effect is amplified by the increased deployment of CCS technologies. The capture CO_2 is stored preferably in ECBM, increasing the methane recovery. As the latter is part of the domestic supply, need for gas import decreases even further. Consequently, the R&D shock on gasifiers has an impact on the indicators related to the energy supply and security. The next table gives the changes between this case and CO_2POL1, a positive value means an improvement.

This complex change in fuel supply affects all indicators which show a small improvement in 2020-2030, but afterwards, when more coal is imported and the ECBM reservoir is filling up, they decrease with 1-2%.

***Table 4-3:* Changes in the energy supply indicators, PRGF case versus CO_2POL1 case**

	1990	2000	2010	2020	2030	2040	2050
Import independency	0.0%	0.0%	0.4%	1.0%	0.4%	-1.1%	-1.8%
Shannon index 1	0.0%	0.0%	0.1%	0.5%	1.3%	1.1%	0.4%
Shannon index 2	0.0%	0.0%	0.4%	1.2%	0.2%	-1.2%	-2.1%
Shannon index 3	0.0%	0.0%	0.4%	1.2%	0.3%	-1.1%	-2.1%

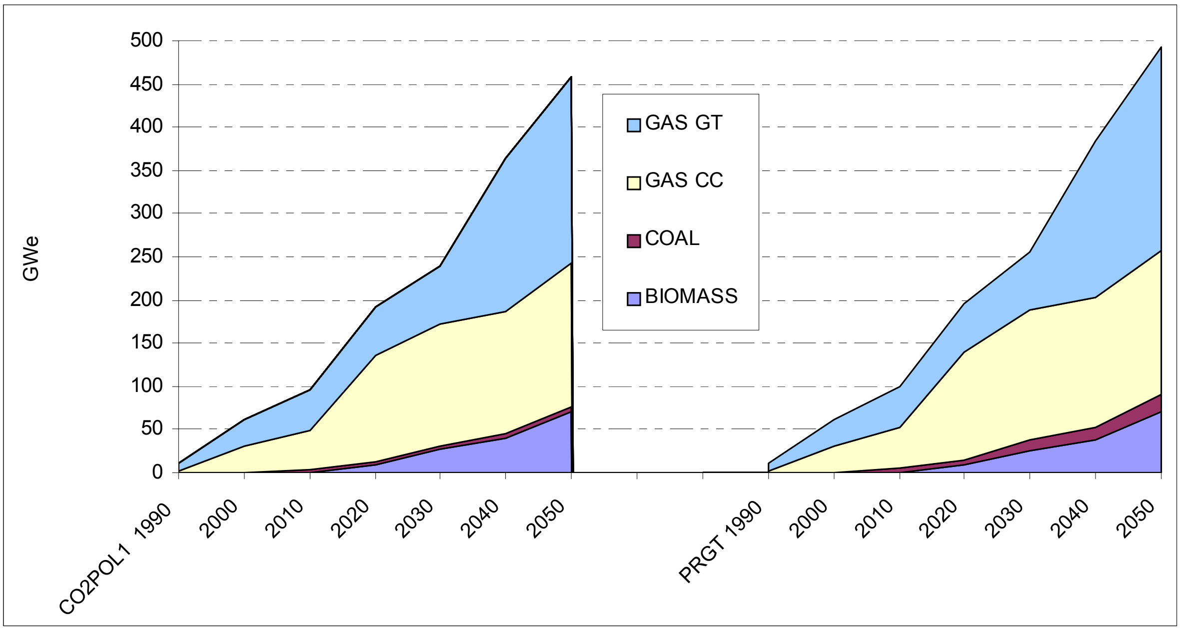
4.1.3. Gas turbines

Gas turbines are modeled in such a way that they can be applied as stand alone turbine for electricity and heat production or as part of a combined cycle. In the latter case, the fuel can be gas, or solids (coal, lignite) or biomass (gasified).

Looking at the deployment of gas turbines, the R&D shock increases the cumulative capacity from 459 to 494 GWe over 1990-2050.

The bulk of the capacity built up is to be attributed to stand alone gas turbines (electricity and CHP), followed by gas combined cycles. The R&D shock introduces wider use in coal IGCC (6 → 19 GWe) and the stand-alone applications (216 → 236 GWe). This may seem not to be a lot, but given the CO_2 tax induced restrictions, this quite a change.

***Figure 4-3:* Cumulative capacity for gas turbines without (CO_2POL1 case) and with (PRGT case) R&D shock**



The increase in capacity in gas-fuelled plants induce also more electricity produced by them (~ 100 TWh in 2030-2040), the increase from coal is less pronounced. The increased gas fuelled production substitutes electricity from biomass and from hydro. This is probably because the load profiles of the power plants (peak or basic production) are different and the mix changes somewhat with equal demand.

The change in electricity production mix is accompanied by a similar change in the primary supply mix, but hardly in total supply level. This is clearly reflected in the indicators: the 1st Shannon index (diversity) reflects the increase in gas consumption which makes the supply mix less balanced; the 2nd and 3rd, together with the import dependency reflect the increased import of gas that makes Western Europe more dependent from that import (negative difference).

***Table 4-4:* Changes in the energy supply indicators, PRGT case versus CO_2POL1 case**

	1990	2000	2010	2020	2030	2040	2050
Import independency	0.0%	0.0%	0.1%	0.2%	0.0%	-1.1%	-0.9%
Shannon index 1	0.0%	0.0%	0.0%	0.1%	-0.1%	-0.7%	-0.1%
Shannon index 2	0.0%	0.0%	0.2%	0.0%	-0.2%	-1.1%	-1.1%
Shannon index 3	0.0%	0.0%	0.1%	0.0%	-0.2%	-1.2%	-1.1%

4.1.4. CO_2 capture from input flow coal/solid

The R&D shock on this CO_2 capture option makes it cheaper, but it only increases the deployment with 4 GWe between 2020 and 2040, i.e. the deployment occurs earlier but not in large quantities. The end capacity is in both cases the same, namely 194 GWe. The increase is found both in solid fossil (+ 1 GWe) as in biomass (+ 3 GWe) fuelled IGCCs.

This increased anticipated deployment of CO_2 capture triggers obviously also more storage. The CO_2 is stored preferentially in ECBM as before, but since the reservoir is finite this option again is filled earlier, and as a consequence storage in EOR also increases somewhat. Over the whole time period the total amount CO_2 captured and stored does not change much, the time profile does however: in 2010-2030 there is more storage, in 2040-2050 there is less and both balance each other. The R&D shock for capture does not lead to more capture or storage, only the timing differs.

This has again consequences on the energy supply, there are some shifts in time in the fuel mix: domestic gas increases in 2020-2030 due to the increased methane recovery, this compensates gas imports (~100 PJ). Later on this is inversed due to the filling up of the ECBM reservoir. Overall, there is little impact on the energy supply indicators since the amounts of energy involved are small.

Table 4-5: Changes in the energy supply indicators, PRCO$_2$COAL case versus CO$_2$POL1 case

	1990	2000	2010	2020	2030	2040	2050
Import independency	0.0%	0.0%	0.2%	0.2%	0.1%	-0.2%	-0.2%
Shannon index 1	0.0%	0.0%	0.0%	0.1%	0.1%	-0.2%	-0.2%
Shannon index 2	0.0%	0.0%	0.2%	0.2%	0.1%	-0.3%	-0.2%
Shannon index 3	0.0%	0.0%	0.2%	0.2%	0.1%	-0.3%	-0.2%

4.1.5. CO_2 capture from gas flow

CO_2 capture from gas benefits from the R&D shock, its capacity built up by 2050 triples almost from 28 GWe to 75GWe. By doing so, it replaces solid fuelled power plants with CCS (coal: domestic and import; and biomass: import) and gas power plants without CCS. This of course has further implications for the fuel supply: less coal and biomass are needed and more gas is needed. This gas comes partly from the increased use of ECBM but mainly from increased import. The changes in supply affect the indicators as shown in the following table: up to 2020 not much is changing, the fuel mix shifts (less coal and biomass and more gas) are substituting and balancing each other, only after 2030 the increased import of gas worsens the energy supply diversity and security with 1.5-1% point

***Table 4-6:* Changes in the energy supply indicators, PRCO_2GAS case versus CO_2POL1 case**

	1990	2000	2010	2020	2030	2040	2050
Import independency	0.0%	0.0%	-0.1%	0.1%	0.1%	-1.6%	-0.8%
Shannon index 1	0.0%	0.0%	0.0%	0.0%	-0.3%	-0.9%	-0.5%
Shannon index 2	0.0%	0.0%	-0.1%	0.0%	-0.3%	-1.6%	-0.8%
Shannon index 3	0.0%	0.0%	-0.1%	0.0%	-0.4%	-1.7%	-0.9%

4.1.6. CO_2 injection

CO_2 injection, as part of the CCS flow, is as mentioned considered separately, and each storage option uses the CO_2 injection device. Applying an R&D shock increases the attractiveness of this device, particularly in the early periods (2010-2020) and storage increases considerably in ECBM. At the same time, because almost all CO_2 can be stored in the ECBM, EOR becomes less attractive in that same period. This is because it is slightly more expensive due to lower economic benefits from the oil recovery. After 2020, the ECBM reservoir is already more filled, so the storage is less than in the CO_2POL1 case for 2030 and 2040. Moreover, EOR is still not attractive enough to take the investment lead over from ECBM, resulting in less storage, meaning that the deployment of the CO_2 injection stammers.

This example shows that for complex technology models, a lower progress ratio not necessary means a wider market deployment in all options, a less balanced trajectory can have a negative effect on the learning e.g. when one of the options does not take over the lead in building up capacity for other (economic) reasons (path dependency).

Further upstream, the change in CO_2 storage also affects the CO_2 capture: there is a switch from gas with CCS to gas without CCS (and to a small amount of hydro). CO_2 capture in industry and fuel conversion is not affected; these CO_2 streams are more or less always available and do not need separate capture.

On the supply side, this results in less gas use (mainly less import, couple of tenths PJ hence resulting is a slightly better supply security) in 2010-2020, afterwards the mix balances out to the original values.

Table 4-7 **Changes in the energy supply indicators, PRCO_2INJ case versus CO_2POL1 case**

	1990	2000	2010	2020	2030	2040	2050
Import independency	0.0%	0.0%	0.1%	0.4%	0.1%	0.0%	-0.1%
Shannon index 1	0.0%	0.0%	0.0%	0.2%	0.1%	0.0%	-0.1%
Shannon index 2	0.0%	0.0%	0.1%	0.4%	0.1%	0.0%	-0.2%
Shannon index 3	0.0%	0.0%	0.1%	0.4%	0.1%	0.0%	-0.2%

4.1.7. Other technologies

CO_2-capture from flue gas from solids

Although CO_2 capture form flue gas coal/solids is expected to see major improvement from the R&D intensity shock, in practice this CO_2 capture technology does show a substantial reaction. Being applied in only one technology, namely advanced lignite fired power plant, there is little room for further deployment, and only 0.3 GWe additional is installed in 2010-2020. Since lignite is no not very favourable emission wise or efficiency wise, nothing changes after 2020 and after 2040 this technology disappears completely. The small change in capacity build-up in this technology has some small side effects resulting in the fact that gas power production takes over some biomass production explaining the difference in emissions and welfare loss.

Heat pumps

The R&D shock induces faster deployment of heat pumps in two of the three sectors (commercial and residential, not in industry) but after 2040 the learning stammers, even with lower specific costs. The commercial sector does not take up further deployment and because of that industry does not follow. This shows that the MIP model can choose another technology path depending on different choices earlier on in the time path.

Fuel cells

A further R&D shock on a technology with already a high R&D intensity, such as fuel cells, generally does not improve the progress ratio enough to make it attractive. It also not appears in the solution; no investments are made. Two more arguments help to explain why this technology remains absent in the solution: probably other policy measures than R&D shocks or learning by searching need to be incorporated: subsidies, hard targets on technology deployment, and the like; secondly the hydrogen system of which fuel cells are an important part may currently be modeled in too crude a way, not reflecting the proper potential and substitution possibilities. Hydrogen pathways are researched in other ongoing projects and from those, additional insights in the requirements for stimulating fuel cell deployment may arise.

Gas steam reforming

The capacity build-up and the deployment of gas steam reforming technologies as a result of R&D shocks barely change over time. Thus, R&D intensity improvement and consequently the better progress ratio only change the specific technology cost, which lead to a very small change in system costs and welfare loss.

Solar PV

The capacity build-up and the deployment of photo-voltaic systems over time barely changes, when an R&D shock is applied. Therefore, R&D intensity improvement and consequently the better progress ratio only change the specific technology cost, leaving these still above the level where the technologies become competitive. Subsidies could probably help this technology deploy on a larger scale.

Wind turbines

As a result of applying an R&D-shock to wind turbines, the capacity build-up and the deployment of wind power systems over time barely changes. Only off-shore wind doubles to 10 GWe, so the R&D intensity improvement and consequently the better progress ratio only change the specific technology cost sufficiently for off-shore wind, and even then only marginally so. Dedicated targets (e.g. renewable electricity targets) would force wind turbines more into the energy system, leading to faster and more learning. The small changes in investment behaviour and timing cause the total system cost to increase slightly and result in about 1.3% more welfare loss.

Electrolyser and partial oxidation of coal

As there are no technology investments for either of these options, even after applying an R&D shock, the impact of such a shock cannot be determined. As part of a hydrogen system, like fuel cells, a CO_2 tax and advanced learning may not be sufficient to ensure the market introduction of such systems.

Residential condensing boiler

The capacities and deployment of boilers do not show a reaction to the R&D shock. Contrary to previously mentioned technologies, the lack of reaction has little to do with the limited effect of a modified progress ratio. Rather, they are constrained for other reasons, e.g. the gas share in residential energy consumption which has a lower and upper growth range in the model based on the current gas use and assumptions about the growth of gas in the built environment. All fuels have such a lower and upper range and the model can constitute a fuel mix satisfying these constraints. It could be possible that a particular fuel already reaches its maximum (or minimum deployment) , leaving no room for the others to increase (decrease) their share.

Gas engine and boiler

Again the R&D shock does not change the deployment, as the needed capacity is apparently satisfied. The available potential could be fixed by other constraints or interactions in the model. Becoming cheaper and being particularly a technology in the end users' sectors, it has a beneficial effect on the welfare loss.

4.2. Conclusions

- R&D shocks have a positive (i.e. price lowering) impact on the specific costs of the technology. However, this does not necessarily lead to increased installed capacity (e.g. Solar PV and Fuel Cells).
- The indirect approach to 2FLC and the used R&D statistics lead to only marginal changes in progress ratios for most of the technologies. So, even beforehand, little impact was to be expected, certainly for those technologies that have already a high R&D intensity that can hardly increase further.
- The data on which this approach is based are very scarce: only three technologies (wind turbines, fuel cells and solar PV) that are rather new to the energy sector. A characteristic of these technologies is the varying share of public R&D and business R&D before and once they become market ripe. Also it is difficult to get enough data to assess the R&D-intensity over a certain period. For several technologies one would have to go to analyse large industrial sectors outside the energy sys-tem (e.g. the aviation industry for gas turbines, or the ICT-industry for cost reduction of electronics).
- The lack of large changes in the results when comparing the CO_2 policy case with the R&D shock cases demonstrates that also the other model and scenario assumptions are extremely important. The CO_2 tax is the main driver for the technological deployment and a different progress ratio on average only has marginal effects.
- Some examples showed also the importance of path dependency: a more favourable learning curve does not necessary means a faster or further going learning path. When

one of the technologies in the cluster does not take over the investment lead, learning may stammer (e.g. CO_2 injection).

- Given the previous elements above, one should be very careful to derive very technology specific conclusions from these MARKAL calculations. With other (equally probable or plausible) assumptions, technologies like solar PV and fuel cells could become attractive as well.
- On the other hand, the learning potentials of renewable technologies like Solar PV modules may be assumed too pessimistic. Or like for hydrogen, the modelling of the hydrogen flow may be too crude. Future work in the Cascade-Mints project will go deeper into the hydrogen technologies.
- The MARKAL SAPIENTIA results indicate that R&D-policy can never stand on its own. R&D can certainly help to reduce specific technology costs, but results show that this is not always sufficient to introduce promising technologies on the market. To get these technologies into the market, addi-tional policy measures are needed. Such market policy measures could be further subsidies for end users or minimum quantity obligations for specific technologies. The combination of the two (a combination of technology push and market pull) might lead to more socially desired outcomes.
- Applying ‘R&D-shocks’ to technologies selected using the R&D-intensity approach led to several insights. In the first place, it appeared that the scenario conditions (especially with regard to applied carbon prices) had much more impact on the model outcomes than enhancing the progress ratio of specific technologies as a result of additional R&D-expenditures. Secondly, only technologies in the power sector showed a noticeable impact from these R&D shocks, indicating that spill-over ef-fects are more pronounced in this sector compared to the other sectors. This sectors, seen their in-herent less homogenous technology representation, are less suited for technology spill-over. This doe however not mean that technology learning can nor occur in these sectors, it doe appear but on a different level and with less spill-over than the key components in the power sector.
- Evaluating the R&D-intensity approach to model technology learning, one can say that the positive news is that it is a feasible approach for large integral energy models. However, several of the assumptions behind this model would need to be revised if one wants to investigate in detail a particular technology and its deployment (potentials, end users fuel mix shares…).
- The impact of R&D shocks (on selected technologies) on the security of supply, expressed by using Shannon indices, is rather limited if one looks over the whole period 1990-2050. Nevertheless some changes in the order of % can occur in particular periods. The negative effects have to do with more import of coal (e.g. in the case of R&D shocks on gasifier, combined cycle boiler) or gas (e.g. in the case of R&D shocks on gas turbines, combined cycle boilers). This means also that a single technology, in particular a learning component, on its own can only have a small effect on overall sys-tem indicators given the same boundary conditions for the rest of the system. Major changes can only occur if a considerable part of the energy system is changed (e.g. a H_2 society or a CO_2 emission free electricity production).
- Finally, ECN work on and with MARKAL proved that even large scale existing energy technology models can easily be equipped with technology learning through the technology cluster approach, covering a large amount of technologies spread over different sectors. This clearly adds to the analytical and scenario performance of the model. However TFLC could not be implemented and a large impact of the TFLC methodology by means of R&D shocks could not be demonstrated as separate from the existing technology learning formulation.

ANNEX 1: SUMMARY OF KEY COMPONENTS CHARACTERISTICS AND PARAMETERS

Key component		PR	unit	INVCOST t=0	initial cumulative capacity	maximum cumulative capacity
model code	**description**			**€/unit**	**10^6 units**	**10^6 units**
CLUBOIL	boiler	0.990	kWe	510	682	50,000
CLUCC1COAL	CO2 capture flue gas coal	0.900	kWe	817	10	1,000
CLUCC2COAL	CO2 capture input gas coal	0.900	kWe	430	10	1,000
CLUCCB	combined cycle boiler	0.950	kWe	500	1.17	1,000
CLUCCGAS	CO2 capture flue gas gas	0.900	kWe	595	10	500
CLUCO2INJ	CO2 injection	0.900	Mton	7.5	100	10,000
CLUCPO	coal partial oxidation	0.900	GJ	18	1	1,000
CLUDSLENG	diesel engine	0.970	GJ	637	5,000	50,000
CLUELCENG	electric engine (transport)	0.950	GJ	1,000	200	15,000
CLUELGENG	ethanol/LPG/Gas combustion engine	0.820	GJ	512	100	10,000
CLUFC	fuel cell	0.820	kWe	2,650	1	1,000
CLUFPSO	FPSO	0.850	GJ	2.03	1,088	15,000
CLUFUSION	fusion reactor	0.950	kWe	6,000	0.01	500
CLUGF	gasifier	0.900	kWe	800	1	1,500
CLUGSLENG	gasoline engine	0.970	GJ	461	5,000	50,000
CLUGSR	steam methane reforming	0.920	GJ	2.4	100	10,000
CLUGT	gas turbine	0.870	kWe	450	31.9	2,500
CLUHINS	heat insulation	0.990	GJ	10	500	500,000
CLUHP	heat pump	0.800	GJ	65	150	5,000
CLUHYDRO	hydro	0.997	kWe	300	23	1,000
CLUNUR	nuclear reactor	0.990	kWe	1,430	118	1,000
CLUPLATF	platform	0.800	GJ	3.6	15,500	50,000
CLURESB	residential boiler	0.990	GJ	5	200	50,000
CLURESCB	residential condensing boiler	0.950	GJ	6	50	50,000
CLUSOLPV	solar PV	0.820	kWe	7,500	0.5	1,000
CLUST	steam turbine	0.990	kWe	300	250	1,500
CLUSUBSEA	subsea system	0.800	GJ	5.33	914	5,000
CLUWIND	wind turbine	0.900	kWe	1,100	5	1,000
ES6	advanced solar	0.920	kWe	3,150	0.1	500
SEH	electrolyser (electricity to hydrogen)	0.900	GJ	19	1	1,000

ANNEX 2A: R&D AND SALES DATA

The following table gives an overview of the data used in the estimation of the PR improvement from R&D shocks. The mentioned sales and R&D data are directly derived from data from the SAPIENTIA information base. If no data was available and the technology is considered for the R&D shock analysis, an estimate of the R&D intensity has been made based on data of similar technologies and on expert opinion.

Key component		**PR_0**	**Cumulative sales 1974-200x**	**Cumulative R&D 1974-200x**	**R&D intensity**
model code	**description**		**M€2000**	**M€2000**	**%**
CLUBOIL	boiler	0.990	767028	94278	10.9
CLUCC1COAL	CO2 capture flue gas coal	0.900	0	280	73.7
CLUCC2COAL	CO2 capture input gas coal	0.900	108	119	52.4
CLUCCB	combined cycle boiler	0.950	9890	1921	16.3
CLUCCGAS	CO2 capture flue gas gas	0.900	140	123	46.7
CLUCO2INJ	CO2 injection	0.900	78	2166	96.5
CLUCPO	coal partial oxidation	0.900	18	1557	98.9
CLUDSLENG	diesel engine	0.970	709080	13408	1.9
CLUELCENG	electric engine (transport)	0.950	944543	3948	0.4
CLUELGENG	ethanol/LPG/Gas combustion engine	0.820	-	-	2
CLUFC	fuel cell	0.820	222	45508	99.5
CLUFPSO	FPSO	0.850	-	-	-
CLUFUSION	fusion reactor	0.950	-	-	-
CLUGF	gasifier	0.900	28373	22753	44.5
CLUGSLENG	gasoline engine	0.970	10836307	68399	0.6
CLUGSR	steam methane reforming	0.920	240	5287	95.7
CLUGT	gas turbine	0.870	166299	88664	34.8
CLUHINS	heat insulation	0.990	-	-	10
CLUHP	heat pump	0.800	-	-	30
CLUHYDRO	hydro	0.997	1632837	28404	1.7
CLUNUR	nuclear reactor	0.990	1021350	180221	15
CLUPLATF	platform	0.800	-	-	-
CLURESB	residential boiler	0.990	-	-	2
CLURESCB	residential condensing boiler	0.950	-	-	10
CLUSOLPV	solar PV	0.820	12619	60357	82.7
CLUST	steam turbine	0.990	745595	117373	13.6
CLUSUBSEA	subsea system	0.800	-	-	-
CLUWIND	wind turbine	0.900	30697	13803	31
ES6	advanced solar	0.920	-	-	50
SEH	electrolyser (electricity to hydrogen)	0.900	19	484	96.2

ANNEX 2B: APPLIED R&D INSTENSITY AND NEW PROGRESS RATIO

CO2POL1 Key component		**new R&D intensity**	**Δ R&D intensity**	**new PR (PR_{new})**
model code	**description**	**%**	**%**	
CLUBOIL	boiler	24	13	0.952
CLUCC1COAL	CO2 capture flue gas coal	91	18	0.849
CLUCC2COAL	CO2 capture input gas coal	74	21	0.839
CLUCCB	combined cycle boiler	44	28	0.869
CLUCCGAS	CO2 capture flue gas gas	71	24	0.829
CLUCO2INJ	CO2 injection	99	2	0.894
CLUCPO	coal partial oxidation	100	1	0.897
CLUDSLENG	diesel engine	4	2	0.964
CLUELCENG	electric engine (transport)	1	1	0.947
CLUELGENG	ethanol/LPG/Gas combustion engine	4	3	0.813
CLUFC	fuel cell	100	0	0.816
CLUFPSO	FPSO	-	-	-
CLUFUSION	fusion reactor	-	-	-
CLUGF	gasifier	76	32	0.809
CLUGSLENG	gasoline engine	3	2	0.963
CLUGSR	steam methane reforming	100	4	0.908
CLUGT	gas turbine	54	20	0.813
CLUHINS	heat insulation	32	22	0.926
CLUHP	heat pump	63	33	0.704
CLUHYDRO	hydro	11	9	0.971
CLUNUR	nuclear reactor	28	13	0.952
CLUPLATF	platform	-	-	-
CLURESB	residential boiler	20	16	0.938
CLURESCB	residential condensing boiler	38	28	0.869
CLUSOLPV	solar PV	96	13	0.782
CLUST	steam turbine	27	14	0.950
CLUSUBSEA	subsea system	-	-	-
CLUWIND	wind turbine	47	16	0.854
ES6	advanced solar	100	50	0.776
SEH	electrolyser (electricity to hydrogen)	100	4	0.889

ANNEX 3: MODELLING CO_2 CAPTURE AND STORAGE

In the used database, there are about 35 technologies in which CO_2 can be captured. This captured CO_2 can then be disposed off in 6 options:

aquifers
depleted gas fields
depleted oil fields
ECBM (Enhanced Coal Bed Methane)
ECBM deep
EOR (Enhanced Oil Recovery)

Each of these options has an estimated potential of CO_2 that can be stored (as in a reservoir):

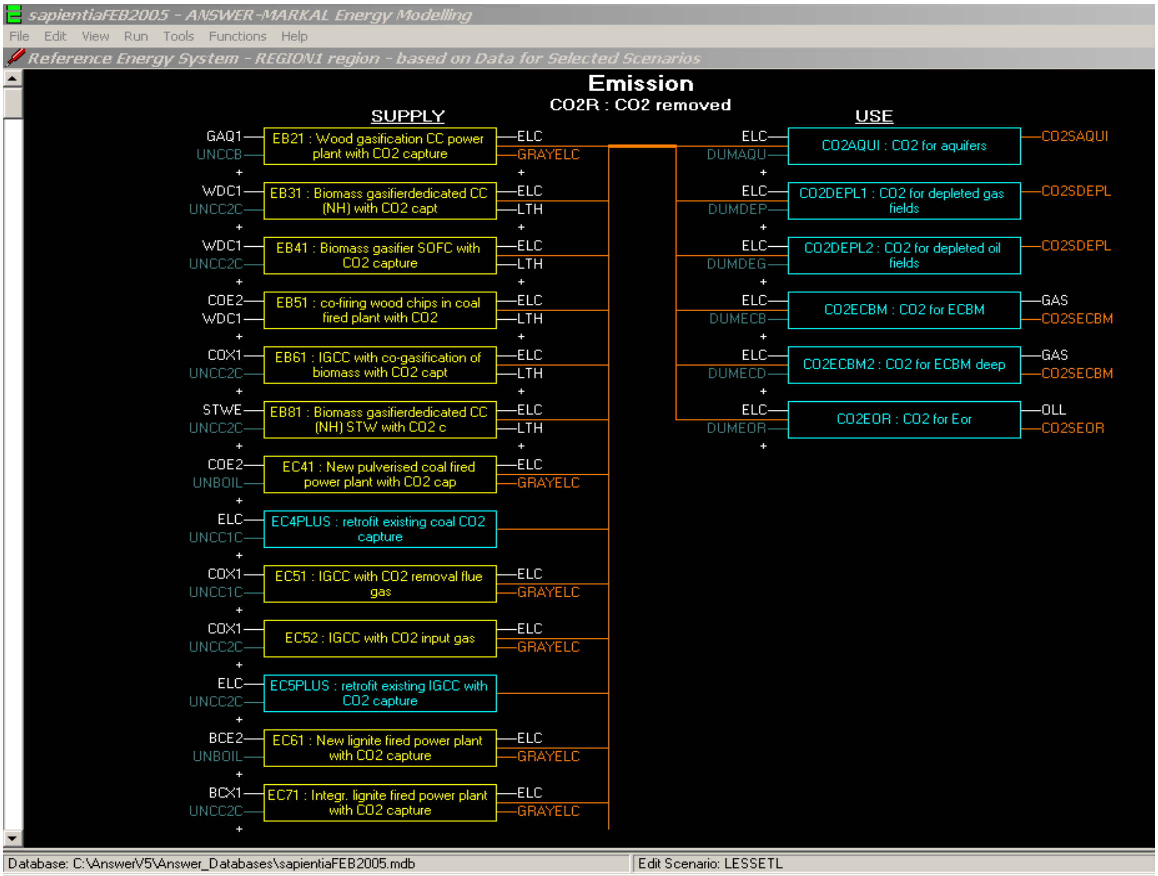
	Mton CO2
aquifers	250 000
depleted gas fields	3 000
depleted oil fields	1 000
ECBM (Enhanced Coal Bed Methane)	15 000
ECBM deep	15 000
EOR (Enhanced Oil Recovery)	17 000
Total	**301 000**

The total amount would be sufficient to store the current emission level (+/- 3300 Mton/year) for about 90 years.

The costs involved with these storage options are as follows:

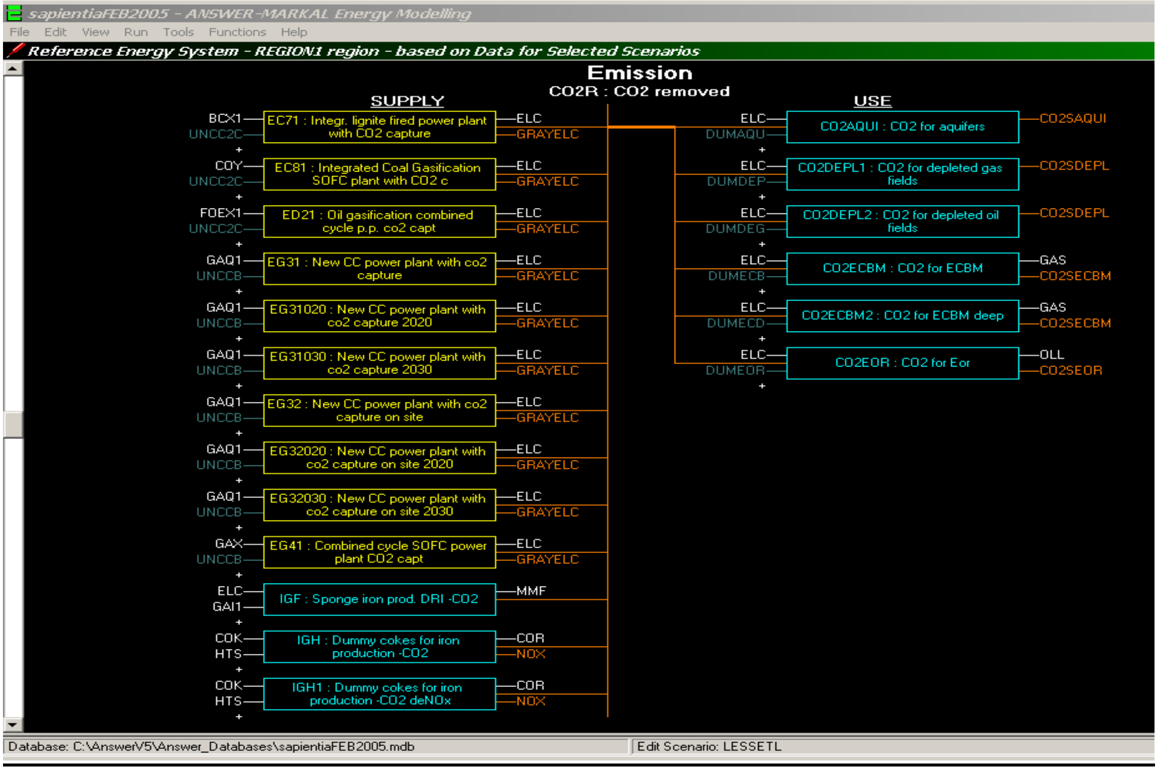
	Investment (€/ton CO_2 stored) (exclusive injection)	Fixed O&M costs (€/ton CO_2 stored)	Variable O&M costs (€/ton CO_2 stored)	energy recovery rate (GJ/ton CO_2)
aquifers	10.00	0.375	0.30	
depleted gas fields	7.50	0.350	1.35	
depleted oil fields	7.50	0.250	1.35	
ECBM (Enhanced Coal Bed Methane)	7.50	0.250	12.50	9
ECBM deep	12.50	0.500	12.50	5
EOR (Enhanced Oil Recovery)	13.33	0.170	0.90	2.22

The following figures represent the technologies in which CO_2 is captured (left hand side) and the option where CO_2 can be stored (right hand side) as they appear in the database. Capture is mainly found in the power sector (large point source of CO_2), but also in industry and fuel conversion (H_2 production).



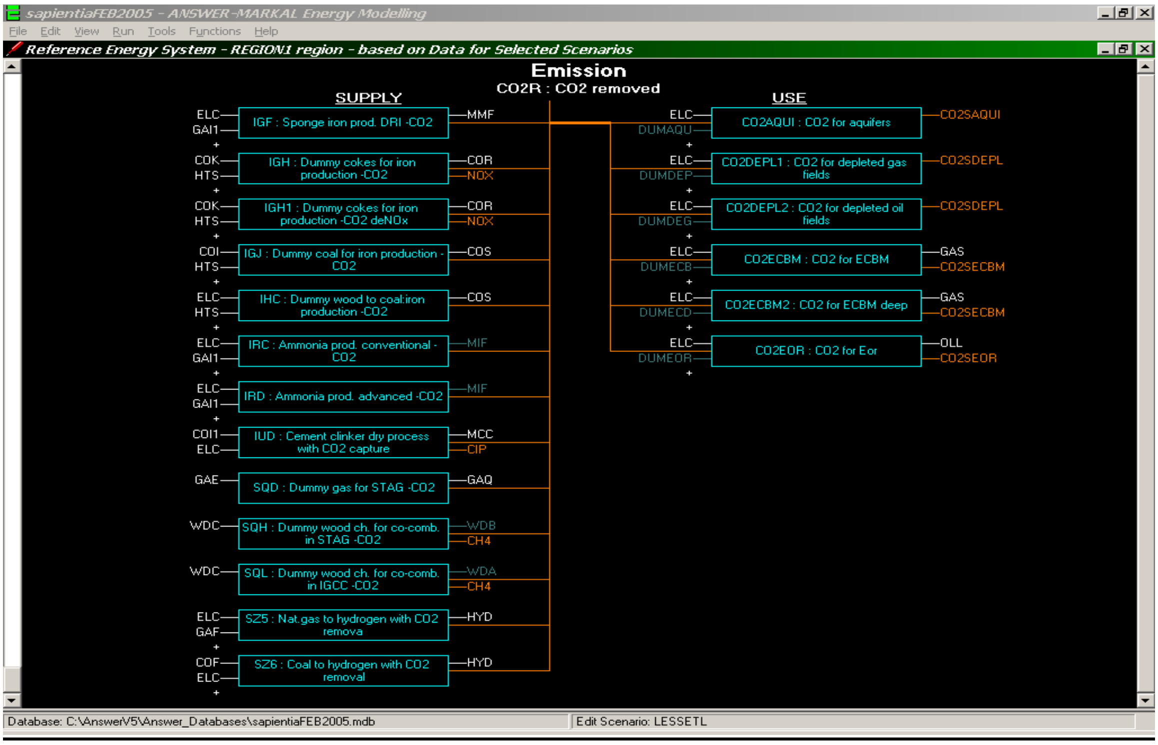
Database: C:\AnswerV5\Answer_Databases\sapientiaFEB2005.mdb

Edit Scenario: LESSETL



Database: C:\AnswerV5\Answer_Databases\sapientiaFEB2005.mdb

Edit Scenario: LESSETL



REFERENCES

Kram, T. et al. (2000) “Technology dynamics in energy systems models with perfect foresight” Int. J. Global Energy Issues, Vol. 14, Nos. 1-4, pp. 48-64.

Seebregts, A.J., Kram, T., Schaeffer, G.J. and Bos, A.J.M. (2000) “Endogenous learning and technology clustering: analysis with MARKAL model of the Western European energy system”, Int. J. Global En-ergy Issues, Vol. 14, Nos. 1-4, pp. 289-319

IEA (2000), “Experience curves for energy technology policy”, OECD/IEA, ISBN 92-64-17650-0

5. PROMETHEUS Results

5.1. Sustainable Development Objectives used in the PROMETHEUS Model

With regard to the list of the agreed sustainable development indicators in the context of the SAPIENTIA project, twelve objectives were retained for the impact analysis with the PROMETHEUS model:

Climate Change:

- Cumulative emissions of CO_2 and CH_4 separately.
- The difference of post-2050 committed temperature and the 1961-1990 global average temperature (15-year commitment period).
- Highest temperature increase over a decade.

Security of Supply:

- Reserves to Production Ratios for Oil and Gas separately at world level.
- World dependence on Middle East oil production.
- Maximum increase in oil and gas prices in any 3-year period of the horizon after the shock has been introduced

Transportation:

- Introduction of low emission passenger cars in total passenger cars market. The low emission vehicles include fuel cells, electric, hybrid and H_2 internal combustion engine cars.

Energy costs to consumer:

- Energy cost reduction to the final consumer for Europe and the Less Developed Countries.

Market Impact:

- A measure of market impact combining technology penetration and cost reductions.

Compared to the list of the sustainable development objectives agreed in the SAPIENTIA Mid-Term meeting, the above set of objectives does not include the following ones:

Climate Change:

- Concentrations of CO_2 and CH_4, because these objectives are expected to be collinear with the “Temperature Change” and the “Cumulative Emissions” objectives, since in PROMETHEUS the temperature is directly linked with the concentrations which in turn are linked with the emissions.
- Sea level rise, for the same reasons of co-linearity as above

Security of Energy Supply:

- Gas and Oil import dependence for Europe, because Europe is mainly oil and gas importer due to its limited natural resources, so it is not expected that an R&D or D&D policy on electricity/hydrogen/transport technologies will show significant impact on this objective. This indicator has been replaced by world dependence on middle east oil objective, on the implicit assumption that such a source will remain more or less insensive.

Air pollution damages on Public Health:

- Prometheus is not capable of including the objectives concerning mortality and morbidity.

5.2. R&D and D&D shocks set up in PROMETHEUS

The R&D and D&D shocks were orthogonally applied, affecting one technology at a time.

Five R&D shocks were applied to each technology. Each shock corresponded to the 5%, 10 %, 15%, 20% and 25% of the technology's projected cumulative R&D in 2025 and it was applied to the whole period 2006-2010. The rational for selecting the year 2025 as the reference year for the policy cost measurement is the fact that many of new technologies have not accumulated significant R&D by 2006, thus defining the shocks as a percentage of this small amount of R&D would probably be unrepresentative of possible budgeting under consideration. Thus, the reference year chosen was set to 2025, a year in which all technologies have accumulated a significant amount of R&D. For each year *t=2006…2010* the R&D shock applied to the technology *i* is given by the following formula:

$$R\&D\_Shock_{i,t} = \left(cumulative\_R\&D_{i,2025} \cdot c\right) \cdot \frac{1}{5} \quad (1)$$

where c=0.05, 0.1, 0.15, 0.2 and 0.25 and denotes the percentages of the cumulative R&D considered in each R&D shock.

The technologies to which the R&D shocks were applied, were:

Technology Description	Short Name
Biomass Thermal	**bf2**
Biomass Gasification plus Combined Cycle	**bgt**
Hydrogen from Biomass Pyrolysis	**bpy**
Coal Conventional Thermal	**cct**
Cogeneration from gas	**chp**
Hydrogen from Coal Partial Oxidation	**cpo**
Building Integrated PV	**dpv**
Gas Conventional Thermal	**gct**
Hydrogen from Gas Steam Reforming (large scale)	**gsr**
Large Hydro	**hyd**
Integrated Coal Gasification	**icg**
Lignite Conventional Thermal	**lct**
Hydrogen from Nuclear High-temperature Thermochemical cycles	**nht**
New Nuclear (4th gen.)	**nnd**
Nuclear (2nd and 3d gen.)	**nuc**
Oil Conventional Thermal	**oct**
Oil fired Open Cycle Gas Turbine	**ogc**
Supercritical Pulverised Coal	**pfc**
Hydrogen from Solar High-temperature Thermochemical cycles	**sht**
Small Hydro (<25MW)	**shy**
Solar Thermal Power Plant Cylindro-Parabolic	**spp**
Hydrogen from Water Electrolysis (baseload electricity from Grid)	**weg**
Wind Turbines Onshore	**wnd**
Wind Turbines Offshore	**wno**
Gas Turbine Combined Cycle & Gas Turbine Open Cycle	**ggc_ggt**
Conventional Internal Combustion Engine Passenger Car	**conv**
Electric Passenger Car & Hybrid Passenger Car	**elev_hybv**
Pre-Combustion CO2 capture (Integrated Gasification Combined Cy	**cgsc**
Pre-Combustion CO2 capture (Coal Partial Oxidation)	**cpsc**
Post-Combustion CO2 capture (Gas Turbine Combined Cycle)	**ggsc**
Post-Combustion CO2 capture (Supercritical Pulverised Coal)	**pssc**
Fuel Cells	**fc**
CO2 sequestration	**co2seq**

On the other hand, the D&D shocks were applied to a smaller number of technologies, primarily to those that can be characterised by fast or medium learning by doing. The technologies to which the D&D shocks were applied, were:

Technology Description	**Short Name**
Building Integrated PV	**dpv**
New Nuclear (4th gen.)	**nnd**
Wind Turbines Offshore	**wno**
Hydrogen Internal Combustion Engine Passenger Car	**thyv**
Gas Fuel Cell Passenger Car	**gfcv**

In principle D&D shocks are easy to perform by introducing exogenously a technology some time at the beginning of the horizon and allowing the learning-by-doing mechanism to determine future technology improvement and uptake. There is however, a problem with costing the policy which must be resolved before any productivity of the measure can be assessed. It would be incorrect to state that the investment cost is an adequate measure except perhaps approximately for very expensive and outlandishly uncompetitive options. Most technologies (even very futuristic ones) will perform useful work (provide energy services or produce energy carriers) throughout their life time hence a more appropriate measure would be an opportunity cost (difference of an expensive and a "cheap" option). The problem becomes to determine an appropriate benchmark. Full present value of the opportunity cost was considered (myopically though in order to avoid outcome based costing as too complicated and potentially confusing).

The D&D costs were equivalent (in terms of value) to the R&D shocks and were performed in five dosages where each one corresponds to the 5%, 10%, 15%, 20% and 25% of the technologies' cumulative R&D in 2025. The D&D cost is measured as follows:

Electricity Production Technologies i:

$$D\&D\_cost_i = 8760 \bullet availability_i \bullet \left(production\_cost_i - production\_cost_{ggc}\right) \bullet \int_0^{LFT_i} e^{-rt} dt \quad (2)$$

where r is the 4% social discount rate and LFTi is the technical life time of technology i. The above formula assumes 8760*availabilityi operating hours for each technology i and calculates the D&D cost in Euro/Kw. The rational behind the above formula is the competition for the base load electricity production that exists between the technology i and a default alternative option (in this case the Gas Turbine Combined Cycle). The production cost difference indicates the additional cost that it is incurred by opting for the more expensive technology i compared to the cheaper benchmark technology Gas Turbine Combined Cycle for the lifetime of the technology i.

Using equation (2) an appropriate capacity of the technology i can be calculated so that the shock is comparable to the corresponding R&D shock in money terms.

Passenger Car Technologies i:

As in the case of the electricity production technologies, equation (2) can be applied as follows in the case of vehicles:

$$D\&D\_cost_i = 15000 \bullet \left(cost\_per\_km_i - cost\_per\_km_{CONV}\right) \bullet \int_0^{LFT_i} e^{-rt} dt \quad (3)$$

Equation (3) assumes that the average annual distance travelled by a passenger car is 15000km and it compares the annual cost per km of the car type *i* with the annual cost per km of the conventional car. The D&D cost is measured in Euro/vehicle and the appropriate number of vehicles can be calculated in order that the D&D cost be comparable with the corresponding R&D cost.

All D&D shocks were applied to the year 2008, which is the middle year in the period 2006-2010.

5.3. Measurement of the Impacts

The following sections describe the formulae used for the measurement of the impacts on the sustainable development objectives.

The general formulation is:

Impact on objective of technology *i* = (Change in objective measured in specific units) / (Change in R&D expenditure or D&D expenditure in euro)

The change in the objective is a model result from introducing a 5-year positive shock on R&D allocated to the ith technology for the whole period 2006 – 2010 or a D&D shock applied to the i-th technology in the year 2008 only. Objectives involving discounting used a constant 4% social discount rate throughout.

5.3.1. Measurement of the impact on climate change objectives

Cumulative CO_2 and CH_4 emissions

Climate change problem is global and the variables of interest are the cumulative world emissions. The formula for measurement the impact on the cumulative CO_2 and CH_4 emissions of the R&D or D&D policy in a technology is:

Impact = (Shock_cumulative_emissions– Reference_cumulative_emissions) / (R&D or D&D expenditure shock)

The GWP factors for CH_4, used in calculations in order to express the cumulative CH_4 emissions in tonne of CO_2 equivalent emissions, were obtained from the IPCC's TAR report on the basis of 100-years commitment horizon.

Temperature change

The simulated climate change depends, therefore, on projected changes in emissions, the changes in atmospheric greenhouse gas and particulate (aerosol) concentrations that result, and the manner in which the models respond to these changes. The response of the climate system to a given change in forcing is broadly characterised by its "climate sensitivity". Since the climate system requires many years to come into equilibrium with a change in forcing, there remains a "commitment" to further climate change even if the forcing itself ceases to change.

According to IPCC's Third Assessment Report the climate system requires many years to come into equilibrium with a change in forcing (i.e. change in emissions and/or greenhouse gas concentrations); therefore, there remains a "commitment" to further climate change even if the forcing itself ceases to change. In the models, a 15-year commitment period is considered, which means that in order to measure more fully the temperature change implications of 2050 concentrations, the results in 2065 should be considered. Thus, the formula for measurement the impact on temperature change is:

Impact = (Shock_temperature_2065– Reference_temeprature_2065) / (R&D or D&D expenditure shock)

Highest Temperature Increase over a decade

The German Advisory Council on Global Change has conducted various surveys in which it concludes that an increase beyond 0.2°C in a decade will potentially have large ecological and economic impacts. As a measure of this damage on ecosystems, an indicator call "the highest temperature increase over a decade" has been introduced. The impact on this objective is measured as:

Impact = (Shock_highest_increase– Reference_highest_increase) / (R&D or D&D expenditure shock)

5.3.2. Measurement of the impact on security of supply objectives

World reserves to production ratios for oil and gas

In the initial set of Sustainable Development Objectives the R/P ratio has been proposed as a measure of sustainability, vis a vis depletable resources. However, in trying to implement this objective in PROMETHEUS it was found that the R/P ratios were heavily dependent on projected discoveries. Since SAPIENTIA does not consider exploration technologies through which the reserves could be influenced it was considered clear and preferable to use an alternative measure incorporating both discovered and undiscovered reserves:

Modified R/P ratio = (reserves + yet_to_find) / production

All quantities are calculated for the year 2050. The impact on this objective is given by the following formula:

Impact = (Shock_Modified_R/P_ratio_2050 – Reference_Modified_R/P_ratio_2050) / (R&D or D&D expenditure shock)

In the case of oil, reserves and production include both conventional and non-conventional oil.

World dependence on Middle East Oil Production

This indicator replaces the import dependence for Europe and it is defined as:

ME ratio = Middle_East_production_2050 / World_production_2050

The impact on this objective is given by using the general formulation:

Impact = (Shock_ME_ratio_2050 – Reference_ME_ratio_2050) / (R&D or D&D expenditure shock)

Maximum Increase in oil and gas prices in any 3-year period

This indicator has been retained from the SAPIENT project, where has been used as the solitary security of supply objective:

Impact = (maximum increase in oil and gas prices in any 3 year period of the horizon after the shock has been introduced - maximum increase in oil and gas prices in any 3 year period of the horizon in the reference)/ (R&D or D&D expenditure shock)

PROMETHEUS incorporates a Middle East productive capacity constraint subject to fluctuations equivalent to those experienced in history as an element in price formation and is therefore capable of producing sufficiently meaningful outcomes. Furthermore it was found to be an objective displaying high differentiation from the other objectives (R&D expenditure on some technologies like clean coal and nuclear was found to be very productive in contrast to their performance in terms of other objectives) and hence susceptible of introducing interesting elements in the R&D / D&D strategy analysis to the extent that different priorities are attached to it.

5.3.3. Measurement of the impact on the introduction of low emission passenger cars

This objective is defined as the share of fuel cells, electric, hybrid and H_2 ICE cars in the world's passenger cars stock in 2050. Thus:

LE_veh = (Fuel_cells+Electric+Hybrid+H_2_ICE) / (total_passenger_cars_stock)

The measurement of impact on this objective is straightforward:

Impact = (Shock_ LE_veh – Reference_ LE_veh) / (R&D or D&D expenditure shock)

5.3.4. Measurement of the impact on energy cost reduction to consumer

This objective is retained separately for Europe and for the developing World. The impact formula is given by:

Impact = (R&D induced total cumulative discounted cost to the consumer - reference total cumulative discounted cost to the consumer) / (R&D or D&D expenditure shock)

All final energy consumers (households and firms) are considered in the calculation. Attention was paid to avoid double counting (i.e. costs of inputs to power generation or hydrogen production should not be included as they would be properly reflected in electricity and hydrogen prices to final consumers). The social discount rate used is 4%.

5.3.5. Measurement of the market impact

In the SAPIENT project, in which this objective has been introduced at the first time, a problem had been identified concerning the measurement of the market impact objective. This arised from the fact that if crude sales (in constant value terms) were taken to be the indicator there was a distinct and legitimate possibility that the market impact arising from an increase in R&D funding proved to be negative. This was the case if the reduction in cost was deeper than the increase in sales often due to some saturation effect incorporated in the baseline (the problem was identified for example in the case of gas turbine combined cycle technologies which penetrate to near saturation levels already in the reference case). In fact, this problem rose in all cases where the implied "elasticity" of demand for equipment was less than one. Clearly, such an outcome made nonsense of R&D budgeting at least in view of this particular objective.

The main problem with the sales indicator was that it did not really constitute an R&D objective. More appropriate measures would be profitability accruing to the agent undertaking the R&D action and resulting from an optimal positioning with regard to aggressive pricing in order to gain market share and cost advantages arising from technological improvements. Furthermore, such advantages in the "real world" are not eternal and areeroded with technological diffusion, the expiry of patents etc.

Consequently the following proxy mechanism was proposed:

- Assume that the reference case improvements are obtained under "perfect competition" conditions that represent zero profits (for the purpose of the exercise).
- Assume that all incremental sales constitute a gain for the agent undertaking the R&D action (other agents retaining their market sales) in perpetuity.
- Assume that the reference case cost remains the reference price of the technology in a way that all the cost reduction implied by the R&D action accrues as profit to the agent also in perpetuity.

Of course the above scheme contains too many restrictive assumptions that clearly do not hold in practice: they imply a mixture of monopoly power with an inability to expand market share beyond net market increments. In this sense it is just as inappropriate as the "sales" scheme. However it enjoys some clear advantages in the sense that it avoids the problems encountered so far, introduces some notion of appropriation, hitherto completely absent from the calculations and hopefully gives better relative measures for productivity of R&D expenditure on different technologies. The latter point is crucial because in the policy analysis we are only interested in relative impacts.

An alternative way of looking at this objective as defined above is that it represents a composite index of two desirable outcomes namely a technological cost reduction and the increase in volume sales. The indicator would then be:

Impact = cumulative discounted ((reference cost –R&D or D&D induced cost)*change in equipment sales volume) / (R&D or D&D expenditure shock)

In the context of the SAPIENTIA project the TFLCs were extended beyond capital costs to cover also fixed O&M cost, variable cost and efficiencies. In order to measure more fully technological improvements the measure was redefined to include all costs of providing a given energy service.. Thus, the impact in SAPIENTIA is measured as:

Impact = cumulative discounted ((reference cost –R&D or D&D induced cost)*change in production volume) / (R&D or D&D expenditure shock)

The production volume change is defined as the increase in electricity production, hydrogen production or vehicle kilometres between the shock and the reference scenario, for the electricity, hydrogen and passenger car technologies respectively. The social discount rate used is 4%.

5.4. PROMETHEUS results on the impacts of the R&D objectives

It was initially envisaged that the mean expected impacts for input to ISPA would be given by the analysis from the large deterministic models participating in the project, whereas the PROMETHEUS stochastic energy model would be used to obtain joint probability distributions of the impacts and other distribution parameters (notably the variance covariance matrices of the impacts). Naturally, this presupposed that the differences in the expected values of the impacts derived from the deterministic models were not large, allowing for compromise values to be decided upon for inclusion in ISPA.

Despite the fact that most models used very similar technology dynamics modules (Two Factor Learning Curves) and that homogenous measures of impacts and standardised shocks were adopted, results differ sufficiently (often widely) between the models. This is mainly due to differences in:

- Model Coverage
- Model Logic (perfect foresight optimisation, simulation, stochastic)
- Underlying assumptions
- Model parameters

Therefore averaging the impacts from the different models would lead to incompleteness and inconsistency when used for integrated policy exploration. As a result, only PROMETHEUS results were finally used for integrated policy assessment, to ensure internal consistency and correspondence between expectations and probability distributions of impacts.

The table below summarises some key PROMETHEUS results on the impact of R&D shocks applied to a selection of power and non-power technologies with respect to a set of sustainable development objectives considered in the SAPIENTIA project.

Table 5-1 Key Statistics for a selection of objectives (Source PROMETHEUS)

SD OBJECTIVE		Biomass Gasification Power Plant	Building Integrated PV	Electric-Hybrid Car	Fuel Cell	Integrated Coal Gasification	New Nuclear	Nuclear	Wind
MARKET IMPACT	Mean	0,55	0,59	0,47	13,08	0,77	0,44	0,17	0,99
	Std. Dev	*0,39*	*0,40*	*0,14*	*27,94*	*0,42*	*0,38*	*0,06*	*0,77*
TEMPERATURE CHANGE	Mean	-0,21	-0,01	-0,04	-0,01	0,16	-0,05	-0,06	-0,17
	Std. Dev	*0,17*	*0,01*	*0,02*	*0,03*	*0,13*	*0,06*	*0,03*	*0,14*
MAXIMUM TEMPERATURE CHANGE IN ANY DECADE	Mean	-0,05	0,00	-0,01	0,00	0,03	-0,01	-0,01	-0,03
	Std. Dev	*0,05*	*0,00*	*0,01*	*0,01*	*0,04*	*0,02*	*0,01*	*0,04*
MAXIMUM INCREASE IN OIL& GAS PRICES IN ANY 3-YEAR PERIOD	Mean	-10,49	-1,80	-158,82	-91,05	-42,49	-30,84	-4,97	-19,57
	Std. Dev	*23,84*	*3,42*	*197,69*	*237,29*	*63,11*	*66,55*	*6,89*	*33,02*
OIL R/P RATIO	Mean	-1,12	0,46	39,76	40,62	0,09	2,06	-0,22	-0,56
	Std. Dev	*2,99*	*0,73*	*36,04*	*81,91*	*12,47*	*6,51*	*1,08*	*4,02*
GAS R/P RATIO	Mean	8,01	0,57	-13,16	-24,90	45,11	37,93	5,13	24,59
	Std. Dev	*12,81*	*2,42*	*9,11*	*33,07*	*36,38*	*41,34*	*3,60*	*25,40*
INTRODUCTION OF LOW EMISSION VEHICLES	Mean	-0,01	0,00	2,08	0,54	-0,01	0,00	0,00	0,01
	Std. Dev	*0,01*	*0,00*	*1,37*	*1,03*	*0,16*	*0,00*	*0,01*	*0,05*
ENERGY COST REDUCTION TO CONSUMER (EUROPE)	Mean	-0,53	1,18	-3,89	-1,33	-1,90	-0,40	-0,94	-3,43
	Std. Dev	*0,45*	*0,50*	*1,43*	*2,35*	*0,75*	*0,47*	*0,22*	*2,32*
ENERGY COST REDUCTION TO CONSUMER(REST OF THE WORLD)	Mean	-0,14	0,08	-0,71	-0,28	-0,99	-0,13	-0,17	-0,47
	Std. Dev	*0,18*	*0,08*	*1,43*	*0,47*	*0,38*	*0,19*	*0,06*	*0,60*
ELECTRICITY COST REDUCTION TO CONSUMER (Europe)	Mean	-0,29	1,16	0,27	-0,09	-1,58	-0,36	-0,84	-3,10
	Std. Dev	*0,29*	*0,48*	*0,16*	*0,15*	*0,67*	*0,42*	*0,20*	*2,02*
ELECTRICITY COST REDUCTION TO CONSUMER (Rest of the world)	Mean	-0,08	0,08	0,00	-0,12	-0,91	-0,11	-0,14	-0,38
	Std. Dev	*0,12*	*0,08*	*0,02*	*0,19*	*0,35*	*0,17*	*0,05*	*0,52*

A first look at this table indicates that some technologies like Nuclear (second and third generation), Integrated Coal Gasification but also the Electric and Hybrid cars display relatively low variability for most targets. Starting with the market impact, the results indicate that with the exception of Fuel Cells impacts on this target are moderate and in general present low volatility across technologies. Fuel Cells are characterised by very high albeit very uncertain prospects. From a risk aversion standpoint, the electric-hybrid car and conventional nuclear power display more attractive prospects, as their market impacts are associated with lower uncertainty (as measured in terms of standard deviation).

In terms of impact on temperature change, biomass gasification and wind power present the largest impacts, but with relatively high variability. Hybrid electric vehicles and conventional nuclear appear more productive in mitigating temperature increases, as even though they display weaker impacts, these are associated with five to eight times less risk. Integrated coal gasification produces the most significant adverse impacts, yet with somewhat higher variability. Similar impacts are obtained for the maximum temperature change in any decade target, but in this case the Biomass Gasification power plant is a less uncertain option.

Impacts on security of supply targets are apparently much more volatile in line with considerable uncertainties surrounding world oil and gas resources and variability in oil prices. Regarding the maximum increase in oil and gas prices in any 3-year period, R&D expenditure on some technologies like fuel cells, electric/hybrid cars, integrated coal gasification and new nuclear is found to be very productive but with highly uncertain prospects. When variability is accounted for, the electric and hybrid cars have the best expectation to variability ratio, followed by 2nd and 3rd generation nuclear power which exhibits restricted impact but is accompanied by very low volatility relative to other options. As regards the oil r/p ratio, R&D on electric/hybrid cars and fuel cells present almost equal security of supply benefits; the former technology however registers less than half the variability, thus suggesting a superior performance. With regard to gas security of supply, new nuclear and wind have very good prospects which are however affected by considerable uncertainty; on the other hand integrated coal gasification presents more attractive prospects demonstrating the greatest impact with moderate uncertainty levels. Conventional nuclear is advantageous to gas security of supply, displaying fairly good prospects with low uncertainty.

Turning to the introduction of low emission vehicles, electric-hybrid cars and fuel cell vehicles (to a lesser extent) make substantial inroads to the clean passenger car market under moderate uncertainty conditions.

Concerning energy and electricity cost reduction to consumers in both Europe and the Rest of the World, integrated coal gasification produces the highest cost efficiency, followed by conventional nuclear. Wind turbines are more efficient for European rather than RoW consumers, but their prospects are somehow moderated by the associated risk in both regions. Fuel cells, new nuclear and biomass gasification power plants display higher variability, of a similar relative order among them. The electric/hybrid car displays important energy cost savings for consumers in both regions. For the electricity costs to the consumer targets however, this technology produces increases in costs for the European consumers and no changes in cost for those in less developed countries. Strong positive impacts to the energy bill are also derived from building integrated photovoltaics for both European and Less Developed countries.

As a broad conclusion of the preceding analysis, it can be argued that technologies which exhibit strong mean expected impacts are not necessarily the optimal candidates for R&D funding, as these prospects may be surrounded by higher uncertainty.

Another key element for the integrated R&D policy analysis as performed in SAPIENTIA, is the co-variance of impacts, as it greatly modifies hedging characteristics. It may also hinder or assist in satisfying given probability constraints. The main sources of covariance of impacts are:

- (Dis)similarities of conditions favouring the impact of given technologies.
- Competition between technologies.
- Technological affinity.
- Clustering and spillovers

Table 5-2 Market impact objective: Technology correlations

	Biomass Thermal	Biomass Gasification plus cc	Hydrogen from Biomass Pyrolysis	Coal Conv. Thermal	Building Integrated PV	Electric/ Hybrid Car	Fuel Cell	Gas Turbine	CO2 capture (gas)	Integrated Coal Gasification	New Nuclear	Nuclear	Supercritical Pulverised Coal	Solar Thermal
Biomass Gasification plus cc	**0.88**													
Hydrogen from Biomass Pyrolysis	-0.19	-0.23												
Coal Conventional Thermal	**-0.63**	**-0.72**	0.29											
Building Integrated PV	0.34	0.37	-0.16	**-0.44**										
Electric/Hybrid Car	-0.02	-0.02	-0.18	0.05	-0.02									
Fuel Cell	0.01	0.01	**0.54**	0.00	0.01	-0.38								
Gas Turbine	**-0.68**	**-0.77**	0.30	**0.91**	**-0.48**	0.07	-0.01							
CO2 capture (gas)	0.26	0.28	-0.11	-0.23	0.10	0.05	-0.01	-0.25						
Integrated Coal Gasification	**-0.71**	**-0.81**	0.33	**0.89**	**-0.47**	0.08	0.00	**0.93**	-0.25					
New Nuclear	**-0.50**	**-0.57**	0.27	**0.60**	-0.20	0.02	0.02	**0.62**	-0.18	**0.64**				
Nuclear	**-0.46**	**-0.52**	0.17	**0.65**	-0.29	0.08	-0.01	**0.71**	-0.18	**0.63**	0.28			
Supercritical Pulverised Coal	**-0.60**	**-0.68**	0.29	**0.80**	**-0.42**	0.05	0.01	**0.82**	-0.19	**0.84**	**0.55**	**0.63**		
Solar Thermal	**0.63**	**0.70**	-0.27	**-0.66**	**0.72**	-0.04	0.00	**-0.72**	0.20	**-0.73**	**-0.46**	**-0.47**	**-0.64**	
Wind Offshore	**0.67**	**0.77**	-0.26	**-0.66**	0.28	-0.02	0.03	**-0.72**	0.30	**-0.74**	**-0.53**	**-0.53**	**-0.62**	**0.64**

The previous table gives the correlation matrix for the market impacts of different technologies, as an indicative measure of their stochastic interdependence as it arises from PROMETHEUS runs. In broad terms, impacts display strong correlations. Clean coal technologies (Integrated Coal Gasification, Supercritical Pulverised Coal) have more closely correlated impacts since they depend on similar configurations for making substantial inroads. The same applies to Fuel Cells and Hydrogen from Biomass Pyrolysis. Integrated coal gasification and gas turbine technologies display strong positively related market impacts, in view of the close correlation of their technical and economic characteristics (technological affinity). On the other hand, the market prospects of wind turbines offshore are negatively correlated to those of integrated coal gasification technologies, as favourable conditions for the former (for instance a carbon constrained world) hinder the market penetration of the latter. Finally, the prospects of new nuclear technologies are strongly and negatively correlated to those of biomass related technologies, a pattern attributed to strong competition between these options.

5.5. Examination of Non-Linearities of Impacts

In the previous discussion R&D impacts were assumed to be linear and homogenous. The figures obtained constitute reasonable approximations of expected impacts if relatively low R&D budgets are considered. If much larger budgets must be analysed, the possibility of non-linearities in the impacts must be taken into account. This has enabled R&D budget exploration, where budget size is a possible policy parameter. In order to obtain concrete quantified information on such non-linearities, a number of R&D shock exercises were applied on 34 technologies affecting one technology at a time using the PROMETHEUS stochastic model. Each shock corresponded to the 5%, 10%, 15%, 20% and 25% of the technology's projected cumulative R&D in 2025 and it was applied to the whole period 2006-2010. 5 D&D shocks were also applied on 5 technologies (building integrated photovoltaics, fourth generation nuclear, wind turbines onshore, hydrogen internal combustion engine passenger car and gas fuel cell passenger car) affecting one technology at a time. The Demonstration shocks were equivalent in terms of value to the R&D shocks. For each shock the PROMETHEUS model was run for 1000 experiments generating a full Monte Carlo set for each technology and each shock size (resulting in 195000 runs). To examine the impact on various targets, a relatively simple and differentiable equation of the following type was fit:

Impact per unit of R&D = f (R&D shock)

Various functional form types were subsequently tested to measure the impact per unit of R&D shock:

Alpha Functional Form: $\boldsymbol{p}(\mathrm{x}) = c_1 \cdot e^{c_2 \mathrm{x}}$

Beta Functional Form: $\boldsymbol{p}(\mathrm{x}) = c_1 \cdot (\mathrm{x}+1)^{c_2}$

Gamma Functional Form: $\boldsymbol{p}(\mathrm{x}) = c_1 + c_2 \log(\mathrm{x}+1)$

Delta Functional Form: $\boldsymbol{p}(\mathrm{x}) = c_1 + c_2 \cdot \mathrm{x}$

Epsilon Functional Form: $\boldsymbol{p}(\mathrm{x}) = \dfrac{c_1}{c_2 + e^{c_3 \cdot \mathrm{x}}}$

, where ***p*** is the expected impact per unit of R&D shock and **x** is the R&D shock.

Variance-Covariance Calculation

The variance-covariance matrix for each objective *i* was calculated on the following basis:

- Given the expected value p of the impact on objective i for technology j, its standard deviation σ(i,j) is calculated by fitting a function of the form:

  $$\sigma_{i,j} = \gamma \cdot \rho_{i,j} + \alpha \cdot e^{\beta \cdot \rho_{i,j}}$$

- Then the variance – covariance matrix for objective i, is calculated from the following relation:

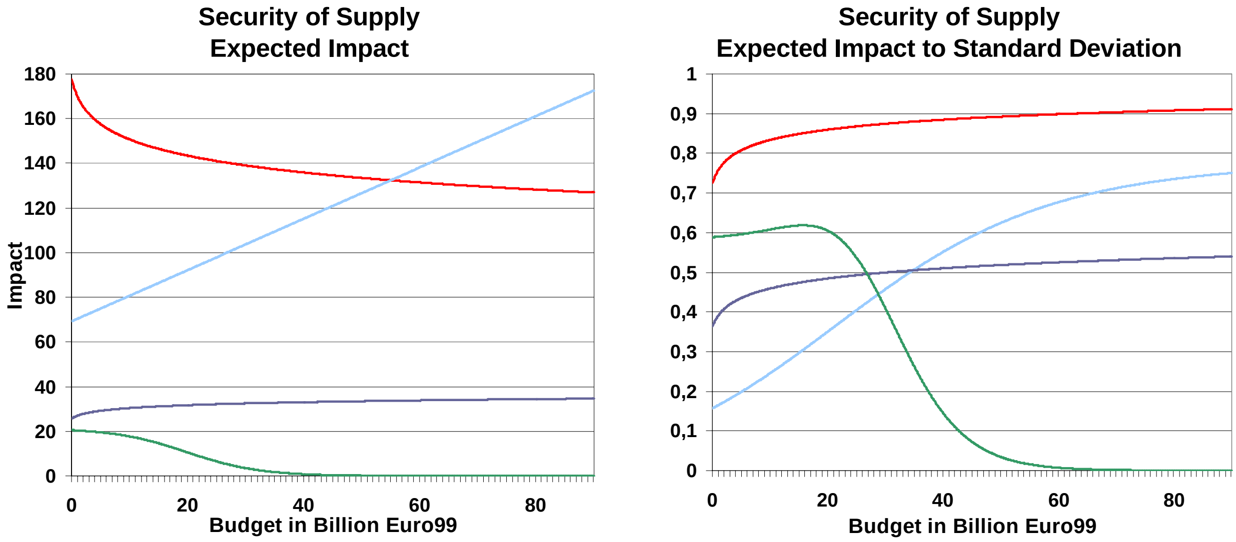
  $$v_{ijk} = corr_{0ijk} \cdot \sigma_{ij} \cdot \sigma_{ik}$$

  - where corr0(i,j,k) is the correlation coefficient of technologies j and k for objective i, obtained from the 10% shock.

These extensive PROMETHEUS non-linearity exercises have revealed diversified (depending on technology and target) modulation of R&D impacts to budget size. Even without considering cross impacts, complexity in the representation of the non-linearities in terms of expectations and other stochastic characteristics (e.g. variance) has increased. Moreover, lock-in effects are reflected on the stochastic characteristics of the impacts announcing additional difficulties in terms of ISPA use. However, no numerical problems arise and convexity is retained. Correlations between impacts were found to be reasonably stable and largely unaffected. In general, results are defendable but impacts appear highly sensitive to budget size.

The graphs below give an indication of the non-linearities encountered and the way they have been treated. The left graph presents the variation of the expected impact per unit of R&D on the security of supply objective for four technologies, candidates for R&D funding. R&D budgeting is effectively a highly speculative activity, implying that considerable uncertainty exists on the efficacy of R&D actions; in this context the graph on the right gives another dimension to the productivity of R&D expenditure on these technologies, providing the mean impacts in terms of standard deviation, thus incorporating notions of uncertainty.

Figure 5-1 Security of Supply impacts: Expectation versus Variability



The first observation is impacts as well as the standard deviations appear to be non-linear (they vary with the budget). The mean impact of R&D on Fuel Cells is sharply increasing with the level of the research budget and so does the attractiveness of this option as measured in terms of the ratio of expected impact to standard deviation. Fuel Cells, being a high risk, high return option, require major R&D efforts to be able to exhibit strong expected impacts at declining uncertainty.

The expected impact of Electric-Hybrid cars on the security of supply target registers decreasing returns to R&D effort. However, the ratio of this impact to standard deviation was found to increase with budget size, suggesting increasing attractiveness of this option in terms of hedging on security of supply.

The productivity of additional research on wind turbines is decreasing, but this option is highly attractive under conditions of hedging, for budgets below a certain amount (approximately 20 billion euro). Beyond this level, its expected impact diminishes. This indicates that wind provides moderate but secure impacts at low levels of additional R&D effort.

E. Integrated R&D Policy Assessment

I. Interactive use of ISPA aimed at involving stakeholders in R&D policy exploration

Leo Schrattenholzer, Marcin Jaskolski,
Asami Miketa and Gerhard Totshnig **IIASA**

Nikos Kouvaritakis (3) **ICCS-NTUA**

1. Introduction

It seems clear that making decision makers feel comfortable with using ISPA requires not only their familiarity with the concepts used to build the model, but also their feeling as much as possible comfortable with the very concept of probability. We shall therefore introduce probabilities step by step, beginning with uncertainty and proceeding to the definitions of expected value, variance and co-variance.

2. Concepts

In this section, we shall introduce probabilities and derived concepts that are required for the understanding of ISPA. As a basis for the introduction of probability, we begin by discussing uncertainty in a formal way.

2.1. Uncertainty

Uncertainty means “not knowing” and therefore tends to have a negative connotation. Nonetheless, we all know that there are many issues in which uncertainty is an inevitable fact of life, and often, we know how to deal with it. Although we assume all readers to have a good intuitive feeling for what uncertainty is, we would like to establish a common ground for the understanding of the ISPA model by discussing certainty and uncertainty in a way that directly leads to the definition of probability.

We therefore begin with those decision-making environments that are considered certain, nearly certain, or at least “knowable”. In those cases, decision making’s paradigm might well be something like “Let us clarify things to a point at which the difference between certainty and uncertainty will not matter for practical purposes and then decide”. For instance, we would not expect a judge who issues a consequential sentence to feel comfortable with the idea that the sentence is based on uncertain evidence. In judicial systems, the threshold in such cases is defined by the term “beyond reasonable doubt”, but apparently nobody has attempted to quantify this criterion. Is it 99%? Or is it 99.9%? Or is it higher? Or lower?

The mere quest for such a quantification of uncertainty requires some introduction into the concept of probability, which we will give in the Subsection 2.2. Here, we just want to try to describe a paradigm that we think is more sophisticated than the hypothetical quote above on the implied possibility of virtually removing uncertainty.

Let us therefore analyze the role of uncertainty in real-life decision making. As a first step in trying to establish agreement on principles, let us note that at least in science, certainty of a fact means the impossibility of the assertion of this fact being untrue. Plausible as this may appear, it also seems obvious that court sentences based on certainty in this sense would have to occur with much lower frequency than in the real world.

Whether such considerations do or don't make judges feel uncomfortable such kind of discomfort would appear characteristic for anyone who is presented with the idea of reflecting on the issue "certainty versus uncertainty" in cases that had been assumed to be at least virtually certain.

Now, the question arises: How to deal with uncertainty? One obvious first step in dealing with it would be to ask: What, if not? More precisely: What are the consequences of what was assumed "almost certain" turning out to be false? Or, expressed in more concrete language: What is the cost of being wrong? Depending on the nature of the event in question, an equivalent question could be: What are the *benefits* of being wrong?

If the event in question influences the outcome of a decision, one might want to compare the cost of being wrong with the benefits of being right (or, respectively, the other way round).

Obviously, for evaluating a hypothetical decision, it would not suffice to simply subtract the calculated cost from the calculated benefit, in particular if either of the two is the consequence of something considered "almost certain". For instance, one might not be overly concerned with a limited loss as a consequence of a decision if a sizeable benefit would be "almost certain".

So far, the points made were qualitative and conceptional. A more quantitative question would be: By how much have the benefits (arising from a favorable outcome) to exceed the cost (arising from an unfavorable outcome) to be to make the decision a good one?

Obviously, the answer to this question strongly depends on the degree of the above "almost". What is therefore needed is something like a "discount factor", which tells us how much to subtract from the benefits of a favorable outcome that is only "almost" certain. This is the place where the concept of probability comes to bear.

2.2. Probability

The concept of probability helps to quantify uncertainty. Certainty is defined as a probability of 100% or one (unity). Closely related to certainty is the concept of impossibility, which is expressed by a probability of zero (0%). The close relation between the two is that the certainty of an event *A* is the same as the impossibility of the logical opposite, *non-A*. Any probability between the two extremes – zero and unity – is referred to as *uncertain*.

Coming back to the question of "almost certain", it would be convenient if everyone would agree that this means (at least) 99%, and if one then could use 1% as the discount factor for correcting the value of a favorable outcome of an "almost certain" event. Several obstacles stand in the way of this simple solution. One is the feasibility of everyone's agreement, the second is that we haven't defined yet what "99% probability" means, and the third one is that even if everyone agrees about the meaning of "99% probability", we don't know (yet) how to measure the probability of an uncertain event.

Theoretical mathematicians care little about these obstacles. They use the so-called axiomatic method, which defines probabilities as real numbers between zero and unity attributed to abstract objects (such as elements or subsets of a set) whereby certain relations between these objects imply certain relations between the real numbers. Any interpretation of this abstract concept would be the responsibility of the user.

Applied mathematicians are not satisfied with merely describing such an abstract model; they attempt to interpret such a model in a language that appeals to non-mathematicians by making reference to the real world. Alas, there is no agreement on interpretation. One important issue on which there is no general agreement concerns the question whether probabilities should be thought of as objective or whether they ought to be understood as subjective. One group of scientists follow de Finetti (1974) and believe that it is most appropriate to consider all probabilities as subjective and to concentrate the efforts of probability theory on analyzing the consequences of given probabilities. But even many of those who believe in the existence of objective probabilities concede that probability theory is more useful than being applicable to only those probabilities that they consider objective.

It would appear risking unnecessary controversy here to encourage readers to take sides on this question[33]. For the discussion of the ISPA model and its application it suffices to point out that the probabilities that are input into ISPA are not the result of physical measurement but of modeling. Their numerical values are therefore uncertain, and different model users might believe in different probabilities. In our opinion, potential users from the decision maker community should not be discouraged by this uncertainty. Quite on the contrary, they should have the feeling that they are presented with a model in which their assessment of probability directly bears on the model results.

One reason why it is useful to define all probabilities as subjective is that in this case, no need arises to formulate different definitions of "objective" and "subjective" probabilities. We therefore present here de Finetti's definition of probability as "degree of belief", measured via the perhaps more familiar odds and betting. A probability of 99% of a given event is therefore defined as the willingness (of a subject) to bet 99 units against one that the event is true. But this definition is not yet complete. For the probability to be 99% and not higher it is also required that the same subject is willing to bet one unit against 99 that the event is not true and, therefore, that the subject is indifferent between the two (hypothetical) bets[34].

As belief is always in the eyes of the beholder, this definition clearly means that each person may have different beliefs and, therefore, that probabilities are subjective. This may be regarded as a *carte blanche* for generating confusion in public discussions by arbitrary probabilities, but only if the difference between arbitrary and subjective is neglected. For instance, saying that the probability of a conventional dice landing on one of its six sides is one-sixth would still be subjective and clearly distinguishable from any unsubstantiated (and thus arbitrary) claim that deviates from this by assigning different probabilities to different sides of the dice. In other words, the subjectivism here concerns only the equal probabilities. Once this (subjective) assumption is made, the probabilities can be calculated in an objective way.

Of course, dice can be constructed in a way that that the assumption of equal probabilities would be implausible. But how to decide whether a given probability is plausible? In the world of subjective probabilities, the answer is: Roll the dice in question until you believe in equal probabilities or in the contrary. Those believing in the possibility that such probabilities can be objective would say: measure the frequencies of each of the six numbers. In our opinion, it is plain that the first one has much more prospects for leading to a satisfactory answer because there is no objective criterion to decide how many times a dice has to be rolled and how big deviations would be permitted to establish one or the other.

The real world knows tests that can be evaluated in a standard way. These tests are very useful and also accepted in practice, but they cannot contribute to defining probabilities because they assume their existence. So any definition of probability that includes such experiments must be circular and therefore scientifically invalid.

To define probabilities via odds may appeal to persons faced with the problem of defining "almost certain" in a quantitative way. Anyway, this definition provides the basis for defining expected values.

---

[33] Readers interested in this issue are referred to de Finetti (1974).

[34] To avoid complications stemming from possible non-linearities of utilities of money (for instance, the loss of one million monetary units might weigh more than a million times more heavily than the loss of one monetary unit), let us assume that the amounts involved in the bet are neither negligible nor huge and perhaps that the cost of betting is carried by some outside source.

2.3. Expected Values

Let us begin defining the expected value of the simple case described above. That is, let us assume that there is a given benefit, say 100 units (e.g., euros) of some outcome that is "almost certain". Let us further assume that we agree that this means that our probability of the outcome is 99%. Then the *expected value* of the benefit is 99 units (euros).

One small thing is missing here to make this definition complete, and this is that for the example to be consistent with the formal definition, it is required to assume that the benefit of the "not-outcome" (which has a probability of 1%) is zero. If that benefit (or cost) is non-zero, the expected value must account for that too. For example, if a loss of 100 units is associated with the non-occurrence of the almost-certain outcome, the expected value becomes

100*99% – 100*1% = 98.

So far, we have avoided to specify any "of what?" in the definition of expected values. The reason is that the answer, "of a random variable, defined for a probability distribution" involves two terms (random variable and probability distribution) that we want to define separately. Intuitively speaking, a random variable can be thought of as a "pay-off" function.

In the example of the "almost certain" event – let us now denote it by "C" – the probability distribution is {C … 99%; non-C … 1%}, and the random variable (pay-off function) – let us now denote it by X – is {X(C) = 100, and X(non-C) = -100}.

In general terms, the simplest case of a probability distribution is a set of events of which one always occurs and where no two events can occur simultaneously[35].

In the case of a dice and equal probabilities of its landing on one of its six sides, the distribution is {"1" … 1/6; … ; "6" … 1/6 }. Let us now define the random variable Y as the numerical value that is on top after rolling the dice, that is Y("1") = 1; …; and Y("6") = 6. The expected value of the random variable Y thus becomes 1/6 + … +6/6 = 21/6 = 3.5. One way of thinking of this result would be to say that 3.5 is the average pay-off if each result of rolling the dice would be accompanied by a pay-off equal to the number on top of the dice. This is the reason, why the expected value is also referred to as average and/or as mean.

Since it will be useful later, let us write down the calculation of this expected value as a formula

$$\sum_{i=1}^{6} Y("i")*p("i")$$

With $Y(“i”) = i$ and $p(“i”) =$ 1/6, the result of this calculation is 3.5.

So far, we have been talking about probability distributions on sets with a small number of elements ("events"). In ISPA and in many other applications, however, we want to consider the probabilities of outcomes that can take any numerical value. For instance, we may want to consider the monetary pay-off of a given policy measure as a random variable. Even if we accept only multiples of euros (and no cents) as acceptable result of a policy measure, the number of possible outcomes becomes large for practical purposes, and a mathematical formula appears to be more efficient for the specification of probabilities of each euro amount than explicit specifications of separate probabilities of each outcome.

Non-mathematicians may find it curious that in such a case, it can be simpler to even increase the number of possible outcomes by admitting any number (in particular numbers with arbitrarily many decimal places) as possible pay-off. In technical terms, this means defining a probability distribution over all (real) numbers or, for instance, an interval on a part of the "real axis".

Let us then assume that the outcome of a policy measure can take any value between $-\infty$ (minus infinity) and $+\infty$ (plus infinity). In this case, it may be possible to define a function $\varphi(x)$ such that

---

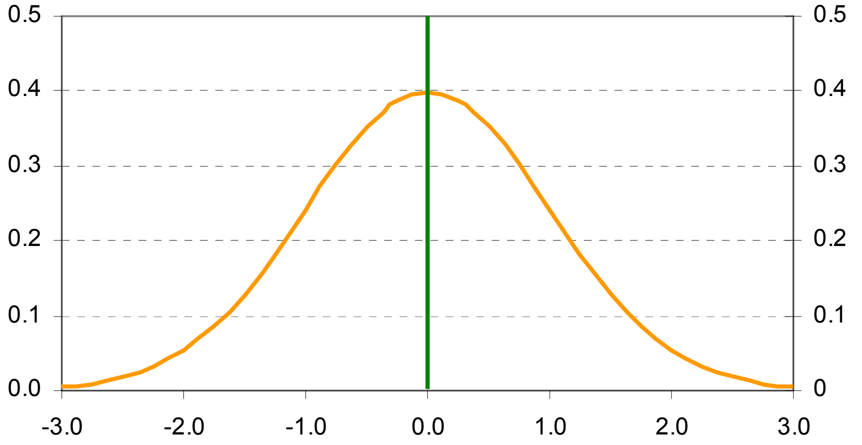
[35] We say here "simplest" because – already in the still simple case of a dice – "even" and "odd" are also events that have probabilities once "equal probabilities" are established. Obviously, in that case, "even" and "2" can occur simultaneously.

the probability of the outcome of a policy measure paying off between 1 and 2 (billion euros, for example) is calculated as the integral[36]

$$\int_1^2 \varphi(\omega)d\omega$$

The function φ(ω) is called *probability density function.* One particularly common form of such a function is the "Gaussian bell curve" (see Figure 2-1).

Figure 2-1 Gaussian "bell curve" (normal probability density function).



In this case, the expected value of a random variable *X* is defined in the following way

$$EX = \int_{-\infty}^{\infty} X(\omega) * \varphi(\omega)d\omega,$$

and the interpretation as an average payoff remains valid.

In this connection, it is often interesting to calculate the probability of a pay-off smaller than a given value37, call it A. This value is calculated as

$$\Phi(A) = \int_{-\infty}^{A} \varphi(\omega)d\omega$$

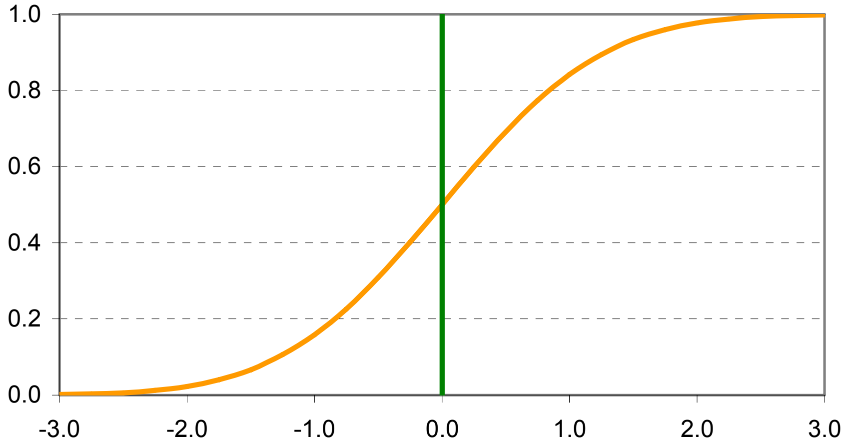
and the Function Φ(A) is called *probability distribution function*. In the case of a Gaussian density function, the function Φ(A) is "S-shaped", that is, its values are always between 0 and 1, ever increasing and symmetric (see Figure 2-2).

---

[36] Readers unfamiliar with integration are advised to note the almost complete analogy between the integral and the summation used for the calculation of the expected value of the above example of the dice and assume that there is no difference between summation and integral.

[37] In reality, "at least as high as a given value" is more common, but the distribution function to be defined here in a moment is traditionally defined as we do it here. As the two versions are obviously closely related, we follow the tradition here.

Figure 2-2 Gaussian probability distribution function



To repeat, Φ(A) is the probability of a pay-off smaller the number A.[38] The probability of a payoff being bigger than A therefore is 1– Φ(A), which approaches zero the higher A becomes.

In many applications – including ISPA – the questions can arise "What pay-off can I expect with a probability of 99% ('almost certainty')?" In formal language, this is the question as to which value of A – let us denote it by A_0 – leads to a probability distribution function value of 0.01, that is $\Phi(A_0) = 0.01$ or, equivalently, $1 - \Phi(A_0) = 0.99$.

The function that yields to different values of A as a function of a given probability is called the *inverse function* of Φ. The following notation for this inverse function is common

$A = \Phi^{-1}(p)$

The value A_0 above can therefore be defined in the following way

$A_0 = \Phi^{-1}(0.01)$

The term used for the number defined in this way is *1%-percentile*, and a more suggestive notation would be $A_{0.01}$. A particularly common percentile is the 50%-percentile, $A_{0.50}$, which defines the payoff that has 50-50 chances of being exceeded as well as of not being reached. In deference of its importance, the 50%-percentile has a name of its own, *median*. In the Gaussian distributions used by ISPA, the median is equal to the expected value.

With this small number of definitions, there are already many things that can be calculated, and many features of ISPA can be understood in a precise way. One concept that is crucial for the use of ISPA, but that has not been explained yet is that of risk.

2.4. Risk

Having introduced the concept of the expected value, the question arises whether a probability of 99% of gaining 100 units is as good as gaining 99 units for certain. Asking differently, the question becomes: "Is it worth going for the gain of an extra unit if there is a 1% risk of receiving nothing?" Here, the term *risk* is used in the sense of the "probability of an unwanted event", and this is how we want to use it here[39]. We can immediately see that this question cannot be answered "correctly" even if most peoples' intuition might suggest that "no" is the right answer.

Again, we encounter a situation, in which subjective assessment comes to bear. Quite analogous to the question "How certain is certain enough?" the question here is something like "By how

---

[38] The probability of a Gaussian-distributed pay-off being *exactly* equal to A is zero. The probability of a Gaussian-distributed pay-off being less than A is therefore the same as the probability of a Gaussian-distributed pay-off being less than or equal to A.

[39] In colloquial language, risk is sometimes used to describe the unwanted event itself, but for that, we would use the term *hazard,* following http://physchem.ox.ac.uk/MSDS/glossary/.

much has the expected value of a random variable to be bigger than an *in lieu* payment[40] to be preferable?" As we have argued above, "subjective" is not the same as "arbitrary". We will therefore present the formal concept of the variance of a probability distribution to shed some quantitative light on this question.

Before presenting a more formal definition, we would like to generalize the question about the preference between an outcome of a random event (also called *lottery*) and a certainty equivalent. The reason is that for any given expected value (or certainty equivalent) there are many different probability distributions that have this value. This means that the term certainty equivalent is not powerful enough to distinguish between two distributions that have the same expected value, but that incur different risks.

Let us describe such a possibility with a real-life example. Assume an investor who considers investments in either stocks or bonds. Let us further assume that this investor's probabilities are such that the expected returns on investment are the same in both cases. Then, the probabilities of higher (or lower) than expected gains can still be distinctly higher for the "stocks" option, and the "bonds" option could be clearly preferable despite of yielding exactly the same expected returns. If this is actually so, we speak of risk-averseness. Conversely, the situation can also be considered as an illustration of the common "no risk–no gain" slogan.

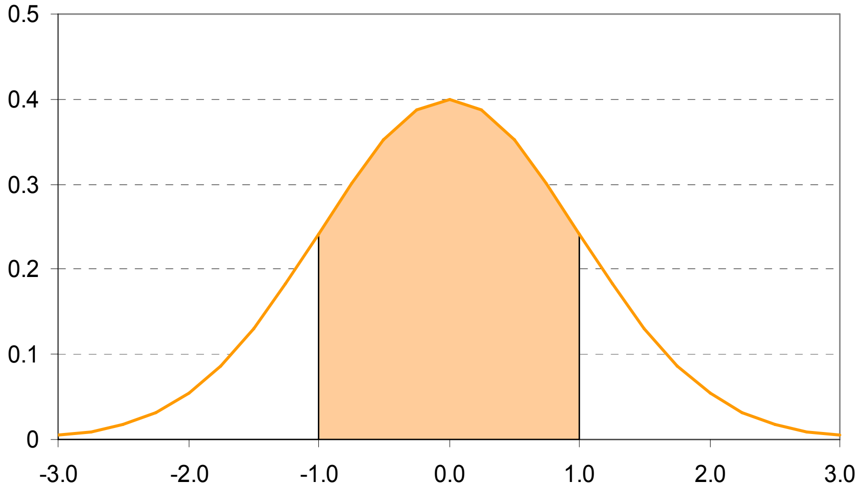
2.5. Variances

Intuitively speaking, the *variance* is a measure of the probability of extreme events. If the extreme event in question is unwanted, the relation between variance and risk becomes immediately clear. More formally speaking, the variance describes something like the average difference between a random outcome and the expected value of a random variable. As we have seen, "average" has to do with the expected value, so the following formal definition of a variance should be intuitively clear:

$$VarX = \int_{-\infty}^{\infty} (X(\omega) - EX)^2 * \varphi(\omega) d\omega$$

One technicality to note here is that the variance measures the absolute (and not the signed) value of a distance by taking the square of the difference. The (positive) square root of the variance is called *standard deviation*. Conventionally, the notation σ is used for the standard deviation. In the often-used Gaussian probability distribution, the probability of the interval [EX-σ, EX+σ] is approximately two-thirds (68%), as illustrated in Figure 2-3 .

Figure 2-3 Probability of the interval [EX-σ, EX+σ].



---

[40] An *in lieu* payment is also called *certainty equivalent*.

2.6. Co-variances

So far, we have restricted our discussion to one random variable at a time. In ISPA, however, where we look at impacts of R&D support of a given set of technologies, different random variables refer to different technologies. The mechanisms determining the impacts of R&D spent on technologies work simultaneously, and the question about possible interdependencies between these random variables arises. For instance, one may ask whether the positive impact of R&D on solar PV is more likely or whether it is less likely in a world in which R&D on wind energy is positive (or, for that matter, if these two random events are independent of each other).

The formal approach to handling this situation quite naturally considers the probability of two random variables coming out on the same side of their respective expected values or on opposite sides.

$$Cov[X,Y]=E[(X-EX)*(Y-EY)]$$

The product between the brackets on the right-hand side is positive if both random variables (*X* and *Y*) come out on the same sides of their respective expected values. Consequently, the covariance is positive if this “is to be expected”. It is negative, if the two random variables tend to come out on opposite sides of their respective expected values.

The numerical value of the covariance depends on the units in which the random variable (e.g., the pay-off or any other impact) is measured. In order to make the resulting number independent of the units of the random variables, the *correlation coefficient* is defined in a way that its value is always between –1 and 1 (including the extremes). The correlation coefficient is conventionally denoted by R^2 and simply calculated by dividing the covariance by the (the product of) the variances of the two random variables.

3. Running ISPA and Interpreting its Results

ISPA can be run at increasingly complex levels. The simplest level involves the technical mastering of running ISPA on the computer (see Section 4 on the interactive use of the ISPA Excel Tool), including the understanding of an ISPA input file. Mastering this level would mean that a user can define ISPA runs that vary only input numbers that can be changed without destroying the consistency between different inputs. This usage mode mainly involves aspiration levels and associated probabilities. More advanced uses of the model involve changing the probability distributions, selecting different objectives as the main objective, and others.

3.1. Describing ISPA without using mathematical formulae[41]

Methodologically, ISPA (Integrating System for Priority Assessment) belongs to the family of stochastic models that optimize multiple conflicting objectives. Let us discuss the defining terms in turn.

“Stochastic” refers to the feature that ISPA includes relationships that are defined in probabilistic terms. This is a very general characterization, and many types of stochastic models exist. For ISPA, this feature means that the impact of spending R&D support on a given technology is defined as a random pay-off with a given probability distribution. Another probabilistic feature of ISPA is that also constraints may be defined in probabilistic terms. For instance, the model user can specify constraints of the kind “the probability of the second objective exceeding the value 100[42] must exceed 90%”.

The term “optimizing” refers to the feature that ISPA considers many possibilities of spending R&D money on different technologies and from these selects one that yields the highest expected impact (described by the main objective) that is possible under the given constraints.

---

[41] Technically interested readers are referred to Kouvaritakis (2002) for a mathematical model description.

[42] In ISPA terms, this value is called *aspiration level*.

Optimizing multiple conflicting objectives reflects a real-world situation in which pursuing one goal infringes on the means of pursuing another goal at the same time. This situation arises in particular, when – as in ISPA – different objectives are measured in different units. If it were for instance possible to "monetarize" all given objectives, all of them could be measured in money terms and the costs and benefits could simply be added.

3.1.1. Building blocks of ISPA

We shall now describe ISPA from the perspective of a user who is interested in the model's results on the impact of R&D support of energy technologies. First, we make the conceptual distinction between controls (control variables) and states (state variables). Controls are the model's counterpart of real-world decisions, for instance, the amount of R&D budget allocated to a given technology. An example of states would be the impacts of a given budget allocation, for instance in terms of the given objectives (costs, emissions, etc.).

The next building block of ISPA is thus the set of objectives. At present, ISPA (Version June 2005) includes five objectives representing five policy goals.

The central "building block" of ISPA consists of a budget allocation, that is, amounts of R&D support of each of a given set of technologies. As more support is assumed to lead to a greater positive impact, ISPA allocates the entire budget that is specified as a budget constraint. The technical description of the fact that the entire budget is spent is that the budget constraint is said to be "binding".

Not all constraints turn out binding in all ISPA runs. An important set of constraints that are often non-binding are the constraints on "aspirations". Aspirations, another "building block" of ISPA, consist of an "aspiration level" (of the impact of R&D spending on one of the objectives) and a minimum probability with which this level is to be reached. If such a constraint is non-binding, this means that the model "volunteers" a higher-than-required probability of satisfying a given aspiration. Such a situation points to synergies between objectives.

The final – mathematically the most important – "building block" of ISPA is the objective function. The objective function, for which a model run identifies the maximum possible value, quantifies by how much the expected impact of a budget allocation exceeds the aspiration level of the *main objective*. The others are called *side objectives*. This presumes that one member of the set of objectives has been distinguished (by the model user) to serve the purpose of serving as the main objective. This may be the objective that is considered by the user as the most important, but this need not be the case. The choice of the main objective simply reflects the user's preferred way of conceptualizing the multi-objective optimization, which works in the way that one the probability of reaching one aspiration is maximized while the other aspirations are just to be observed.

From the perspective of risk avoidance, this means that if a user has a clear quantitative idea about risks to be avoided[43] with respect to one of the objectives, that objective is appropriately chosen as a side objective.

3.1.2. Base-Case Data

The overall logic of the functioning of ISPA is already well described by the description of the building blocks in the preceding Subsection 3.1.1. Still, an important part of the model description is still missing as long as the objectives and technologies have not been described.

As with many descriptions of models of this kind, it is not always possible to unambiguously distinguish between ISPA and its input data. However, such a distinction would be mostly of theoretical value, and what matters for the users is which parts of the computer file with the model inputs they could change in the course of working with the model according to their needs.

In the sequel, we shall therefore refer to data in those cases where we either expect that users should feel in command of changing them if they want[44] or where we exactly describe the data as

---

[43] Remember that risk is understood here as "probability of a negative outcome ".

given from some outside source. Everything else, such as the number and the names of technologies, for instance, should be considered as part of the model.

The R&D budget

For illustrative purposes, the base case of ISPA assumes an R&D budget of € 10 billion (10^9). The interpretation of this figure is that it is spent once, and the (random) impact on the objectives is calculated by ISPA.

The original version of ISPA (until June 2005) featured a linear impact of the R&D budget. The later, improved, version permits for a non-linear response to the total R&D budget. For the Section 2, *An Introduction into Basic Concepts,* the nonlinear version of ISPA was used as this was the version available at the time of writing. For the Section 4, *Interactive use of ISPA,* the latest available non-linear version was used.

It may appear natural to policy makers to investigate the impact of increasing or decreasing this budget. Of course, this is a legitimate question to the model, but two points should be noted.

First, since ISPA is linear, a 10% increase of the budget creates a 10% increase of the impact. Although impact is one result and probabilities are another, we want to caution against possibly exaggerated expectations from such additional model runs.

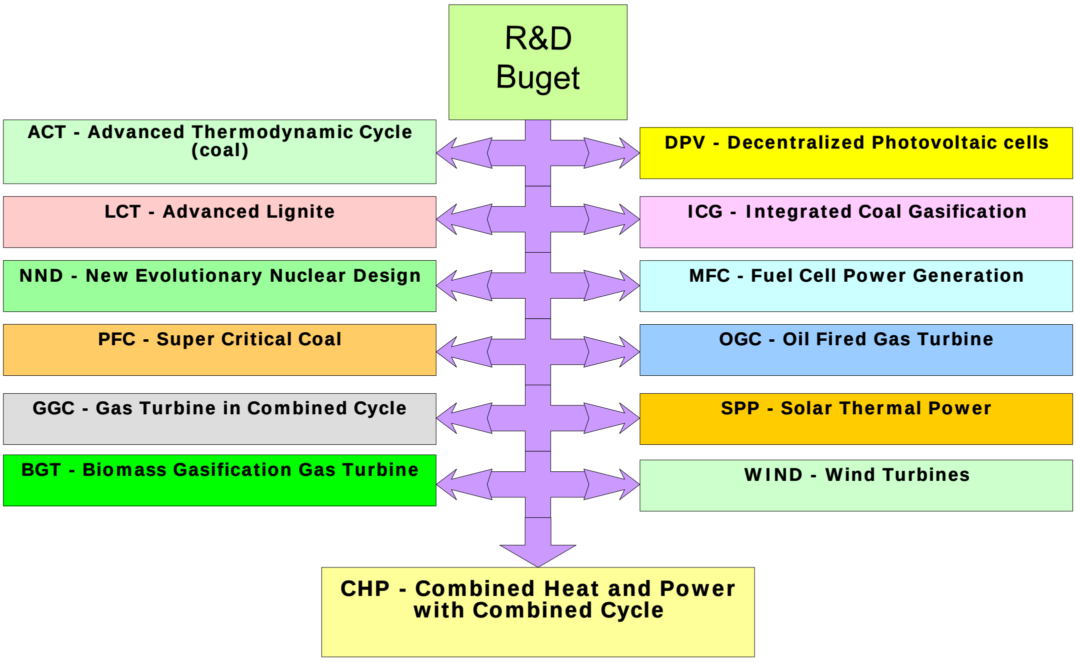
Second, the non-linearity of ISPA means that for aspirations very far away from those included in the base case, the impacts may not be correctly calculated by the model. For instance, if a user were to analyze the R&D necessary to reduce carbon emissions by 100% (that is, to zero) with a probability of 90%, ISPA should not be used to calculate the budget requirements for that aspiration.

But these two points are merely caveats, and we include a documentation of ISPA sensitivity runs with respect to the budget constraint below.

Technologies

In ISPA, 13 different power generation technologies are candidates for R&D support. They are presented in Figure 3-1 .

Figure 3-1 Technologies included in ISPA.



---

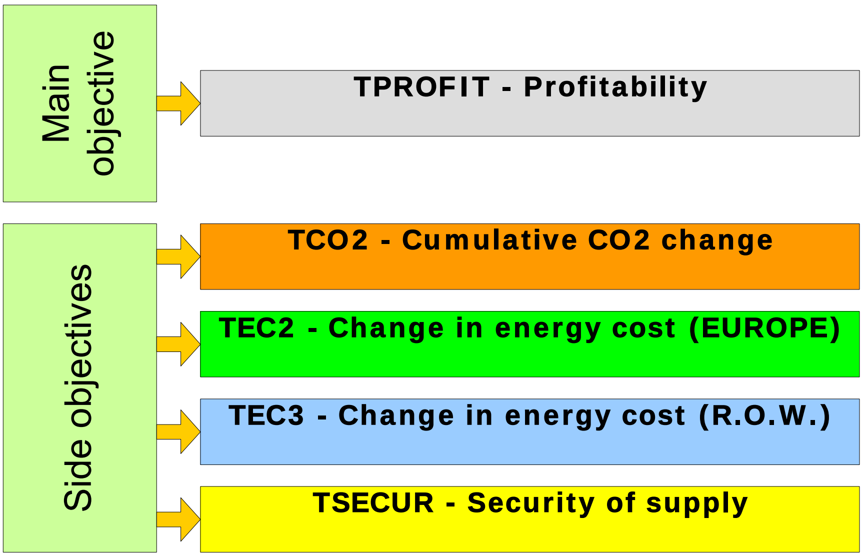
[44] It may happen that readers in some instances are unsure as to which inputs they are in command of. These readers might receive clarification in this respect by studying the description, further below, of base-case results and of a guided sensitivity analysis.

No input data other than their names are connected with the technologies themselves.

Objectives in ISPA

There are five policy objectives in the ISPA model. They are summarized in Figure 3-2 .

Figure 3-2 Objectives included in ISPA.



In contrast to technologies, the objectives and the units in which they are measured need to be defined, and their aspirations must be quantified. This is done in the following table:

Table 3-1: The five objectives of ISPA

Objective	*Units*	*Short description*	**Definition**
TPROFIT	Billion (10^9) euros	Profitability	(Reference cost – R&D-induced cost)*Change in sales volume, discounted
TCO2	Billion (10^9) tonnes of CO_2	Change of total CO_2 emissions	Change in cumulative carbon emissions
TEC2	Billion (10^9) euros	Change in energy cost to the consumer in Europe	R&D-induced total discounted cost to the consumer) – (reference total discounted cost to the consumer)
TEC3	Billion (10^9) euros	Change in energy cost to the consumer in the rest of the world	*Same*
TSECUR	Percent	Security of supply	(maximum increase in oil and gas prices in any 3 year period of the horizon after R&D expenditure) – (maximum increase in oil and gas prices in any 3 year period of the horizon in the reference)

The main objective

More as an illustration than as the result of our assessment of the relative importance of the objective we chose *Profitability* as ISPA’s *main objective*. We like to repeat at this point that anyway, the significance of the main objective is mostly procedural or even technical. It just suggests that it is suitable for maximizing it or, equivalently, that the side objectives can be thought of involving threshold values that are important to achieve with a given (high) probability, but for which it is perhaps less important to “overachieve”.

Aspirations

As we have said above, aspirations consist of an “aspiration level” (of the impact of R&D spending on one of the objectives) and a minimum probability with which this level is to be reached. The numerical values defining the aspirations are given in the following table:

Table 3-2 ISPA aspirations.

Objective	*Aspiration level*	*Probability threshold*
TPROFIT	10	–
TCO2	0	90%
TEC2	10	90%
TEC3	10	50%
TSECUR	0	50%

Note that the probability of a € 10-billion profit is maximized, and no threshold is therefore given for this objective, which figures as the main objective. Note also that we put the aspiration level of the base case at the amount that we specified for the R&D budget. The result of the base case therefore will tell us the (maximized) probability that our R&D spending will pay back in terms of the profit objective alone.

Mean Random Impacts

We begin the presentation of the probability distributions describing the impacts of R&D spending by presenting the expected (average) impacts for each technology and each objective in Table 3-3 .

Table 3-3 Average impacts (rounded to two decimal places).

	TPROFIT	TCO2	TEC2	TEC3	TSECUR
ACT	0.08	-0.04	0.22	0.06	1.71
BGT	10.29	0.67	2.28	0.64	8.78
CHP	0.69	-0.05	0.51	-0.08	-3.19
DPV	3.18	0.09	-0.53	-0.31	0.47
GGC	10.56	0.44	2.86	1.52	-6.46
ICG	3.88	-0.18	1.30	0.47	8.34
LCT	0.20	-0.07	0.73	0.06	0.85
MFC	3.15	0.04	0.07	0.10	-2.28
NND	0.02	0.01	0.04	0.01	0.17
OGC	0.88	-0.22	-2.29	-0.46	-20.71
PFC	3.07	-0.42	2.16	0.82	16.12
SPP	6.83	0.13	0.03	0.04	1.17
WIND	22.29	0.85	2.20	0.58	6.26

These input data come from runs of the PROMETHEUS model. Unlike the aspirations, which we feel are completely in the domain of policy makers, the expected impacts represent results obtained within the SAPIENTIA project. Although it users can change these numbers for each model run, it is recommended that this is done either on the basis of new information about the expected impacts or in performing sensitivity analysis. In any case, it should be kept in mind that the description of random impacts is not complete without the specification of the co-variances. (See the description below.)

Let us briefly characterize the technologies included this table[45] by commenting on their expected impacts.

ACT – Advanced Thermodynamic Cycle (Coal). Advanced thermodynamic cycle is a novel power generation technology using coal as energy input. R&D support of this technology is expected to have weak impacts on each of the objectives. In most cases the impact has positive value, but since ACT does not include carbon, it has a negative impact on CO_2 emissions.

---

[45] A more detailed discussion of the Prometheus results is given in other parts of the overall SAPIENTIA report.

BGT – Biomass Gasification Gas Turbine. Power plants and CHP (combined production of heat and electricity) plants based on biomass gasification (BGT) technology are equipped with (among others) a biomass gasifier and a gas turbine, which combusts the gas produced by the gasifier. Support of BGT is expected to have strong positive impacts on the profitability and security of supply, but also positive impacts on the other objectives.

CHP – Combined Heat and Power with Combined Cycle. Combined Heat and Power (CHP) is a coupled-production technology. Heat and electricity are produced in "cogeneration", which includes both steam and gas turbines ("combined cycle"). Input fuels to this technology are coal and natural gas. Support of CHP is expected to have a medium-sized negative impact on the security of supply. It has also negative impact on cumulative CO_2 emissions and the energy cost to the consumers outside Europe.

DPV – Decentralized Photovoltaic Cells. Decentralized photovoltaic cells are relatively small units that convert solar energy into electricity for individual consumers. The technology is very clean, but it is still expensive. The energy input incurs no fuel costs, but the capital cost per installed capacity is comparatively high. The strongest positive impact of supporting this technology is on the profitability. Supporting this technology is expected to lead to an increase in energy cost to consumers both inside and outside Europe.

GGC – Gas Turbine Combined Cycle. This technology converts chemical energy embodied in natural gas into electricity using a steam turbine in addition to the gas turbine. GGC turbine is characterized by relatively low capital cost and by a very high (positive) impact on profitability. On the other hand, developing this technology further is expected to lead to a decrease in the security of supply. R&D allocation to GGC has a comparatively small impact on energy cost. The weakest impact is on the CO_2 emission change, which means that GGC emissions are close to business-as-usual with or without R&D support of GCC.

ICG – Integrated Coal Gasification. Power plants based on ICG technology are equipped with a coal gasifier. Supporting ICG is expected to have strong positive impact on the security of supply, but it also favors profitability and security of supply in a significant way. Its support has a weak negative impact on the cumulative CO_2 emissions, however.

LCT – Advanced Lignite. LCT is based on a steam turbine cycle with combustion of lignite. Support of this technology is expected to have a weak negative impact on cumulative CO_2 emissions and a weak positive impact on the other objectives.

MFC – Fuel Cell Power Generation. Fuel Cell technology is regarded as the technology of the future. MFC generates electricity and heat using fuel cells. Input fuels are usually natural gas or hydrogen. Using natural gas requires a fuel processor[46], which implies higher capital costs, but the fuel costs are much lower than those of hydrogen. R&D support of this technology is expected to have medium-sized negative impact on the security of supply, and a medium-sized positive impact on profitability. It is also expected that supporting this technology will have weak positive impact on cumulative CO_2 emissions as well as on energy cost to consumers both inside and outside of Europe.

NND – New Evolutionary Nuclear Design. This technology is based on nuclear power and it is expected to have weak impacts on all objectives.

OGC – Oil-fired Gas Turbine. As a consequence of using oil as an input fuel, supporting OGC is expected to have very strong negative impact on the security of supply. It is also assumed that it will have a weak positive impact on profitability and a weak negative impact on both cumulative CO_2 emissions and on energy cost to consumers both inside and outside of Europe.

PFC – Super-critical Coal. PFC includes a steam turbine operating with super-critical steam. Support of this technology is expected to have a strong positive impact on the security of supply, a medium-sized positive impact on profitability and on energy cost to European consumers, and a weak negative impact on cumulative CO_2 emissions.

---

[46] A fuel processor here is a device that converts natural gas into hydrogen. A chemical reaction of natural gas and steam (or oxygen) is used in this process.

SPP – Solar Thermal Power. SPP converts solar energy into heat, which generates steam for use in a steam turbine. R&D support of this technology is expected to have a strong positive impact on profitability, and weak positive impacts on the other objectives.

WIND – Wind Turbines. WIND is one of the most dynamically developing renewable energy technologies. Its support is expected to have very strong (the strongest of all technologies considered here) positive impacts on profitability, a medium-sized positive impact on the security of supply, and weak positive impacts on the other objectives.

Variances and Co-variances

The normal way to present variances and co-variances is in form of a matrix, the diagonal of which contains the variances. The other elements $a_{i,j}$ ($i \neq j$) contain the co-variances of the random variables X_i and X_j. The indices i and j denote technologies. Since ISPA includes five objectives and 13 technologies, five 13x13 variance/co-variance matrices are needed as inputs.

It seems important to note that the elements of variance/co-variance matrices cannot be chosen freely, but must conform to some mathematical properties. Changing them arbitrarily would therefore be likely to introduce mathematical inconsistencies and lead to meaningless model outputs.

We reproduce these matrices as tables in the appendix. Here, we just discuss some of their elements that we consider important.

Let us begin with the "profitability" objective. There we find large uncertainties (high variances) for the mean impacts of R&D on wind turbines (WIND), solar thermal power (SPP), and biomass gasification gas turbines (BGT). The qualifier "high" is of course relative and subjective, but has an obvious yardstick for being judged: the mean impact. To illustrate: The expected profitability of putting 10 billion euros into R&D on wind power is (roughly) 22 billion, and the variance of this random impact is (roughly) 286 billion. As we have noted above, the interpretation of this is that with a probability of (roughly) two-thirds, the profitability of R&D on wind will fall between 308 (22+286) and –264 (22-286) billion.

The variance-covariance matrix for the "Profitability" objective informs that there is a strong (positive) relation between the impacts of supporting wind turbines and biomass gasification gas turbines, described by a value of 63.2. The impact on profitability of supporting wind turbines is also positively correlated with that of Solar Thermal Power (20.2) and that of Decentralized Photovoltaic Cells (11.2). Negative correlations between the profitability of R&D of wind turbines are less pronounced. In our reference scenario, an example of such a correlation is with the profitability of supporting gas turbines in combined-cycle (9.7). One can notice strong (negative) correlation between the impacts on the "security of supply" objective of R&D spent on oil-fired gas turbines and combined heat and that spent on the combined generation of heat and power.

Note that these are just a few examples of many possible characterizations of input data on the random impacts of R&D spending on technologies. The origin of these numbers is the PROMETHEUS model. Its results and their interpretation are documented elsewhere (Kouvaritakis, 2002).

3.2. Interpreting ISPA Base-case Results

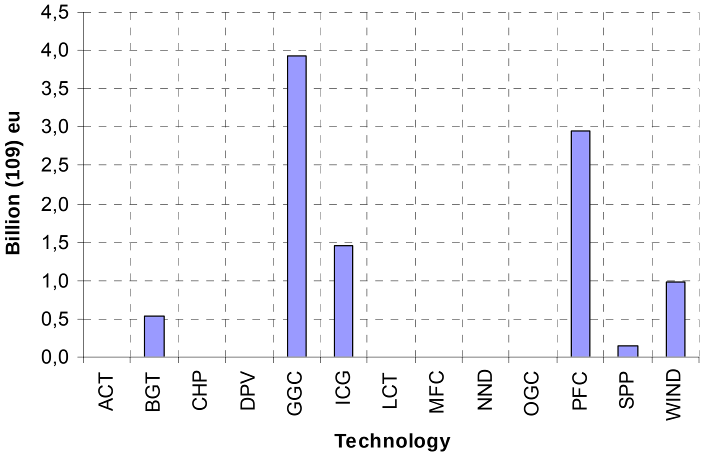
The main output of ISPA is the optimal (feasible) R&D budget allocation, which is defined as the R&D budget allocation that maximizes the probability to achieve the quantitative goal (also known as objective threshold) of the main objective while satisfying the aspirations with respect to the side objectives. If the aspirations are set too high, that is, if the R&D budget does not allow meeting the aspirations no matter how improbable it becomes to pass the threshold for the main objective; ISPA returns the message "solution infeasible". As we shall illustrate below, a typical way of running ISPA is to probe the model by increasing aspirations step by step until infeasibility results[47].

---

[47] Note that increasing the threshold for the main objective further and further does not lead to infeasibility, just to lower and lower probabilities of reaching it.

The resulting budget allocations of the base case are shown in Figure 3-3 .

Figure 3-3 R&D Budget allocations for the base case of ISPA.



As it can be observed in Figure 3-3 , only six energy technologies out of 13 receive R&D support under base-case conditions. The other technologies are expected to neither sufficiently contribute to either increasing the profitability of R&D nor to increasing the probability of meeting the aspirations with respect to the side objectives.

Before trying to interpret these results, it appears useful to check which constraints are binding. This is best done with Table 3-4 which shows the expected impacts on the side objectives, and the probabilities of reaching them.

Table 3-4 Random impacts and aspirations in the base case.

Objective	Expected impact	Aspiration level	Probability	Aspiration probability
TCO2	1.44	0	0.90	0.90
TEC2	22.87	10.00	0.97	0.90
TEC3	10.00	10.00	0.50	0.50
TSECUR	45.28	0	0.68	0.50
TPROFIT	84.65	10.00	0.99	Maximized

It turns out that two aspirations are binding, that is, that (i) carbon emissions must not increase with a probability of 90% and (ii) that energy cost outside Europe must not increase by more than 10 billion euros. Note that carbon emissions can still be expected to decrease by 1.44 billion tones because the required probability of their not increasing is 90%. The probability requirement for the energy costs outside Europe was required to be only 50%, which results in the actual impact of exactly the aspiration level.

From this we can now say that the probability of profitability was constrained by the two aspirations with respect to carbon emissions and to energy costs outside Europe. To find out how strongly the optimal result was influenced by these two aspirations, a sensitivity analysis must be performed. We report the mechanics involved in a sensitivity analysis and its results below (Subsection 3.3).

GCC, gas turbines, receive almost 4 billion euros, the biggest share of the total R&D budget of 10 billion euros. Super-critical coal and integrated-gasification technologies are the receivers of the next biggest R&D budget shares.

One important modeling result gives information concerning the marginal impact of spending one more unit of R&D support. The technical term for this piece of information is *marginal cost* or *shadow price*, both terms describing the same thing, i.e., by how much the value of the main objective changes if the limit given by a constraint is changed. From this definition it follows that each constraint has a shadow price, which can be zero, in particular if a constraint is non-binding. The normal case is that a shadow price is positive if and when a constraint is binding. Speaking generally, the shadow price is convenient to interpret if the objective function is defined in monetary terms because in that case, it would tell us the cost (in euros) of tightening the constraint by one unit. In the case of ISPA, shadow prices are defined in terms of percentage points of additional probability to exceed the aspiration level of the main objective.

For the base case and its budget constraint, the result is that the probability of the profitability exceeding 10 billion euros increases by 14 percentage points for an additional billion of euros spent on R&D. But this is just the literal interpretation, which follows from the specific units chosen. Since the probability of meeting the aspiration level of the main objective is already as high as 99.12 percent, the more appropriate interpretation would be to say that increasing this by 0.01 percentage points (to make it 99.13) will roughly cost 700,000 euros[48].

The usefulness of this piece of information may be assessed differently by different model users, but in any case, it does not substitute for a more complete sensitivity analysis.

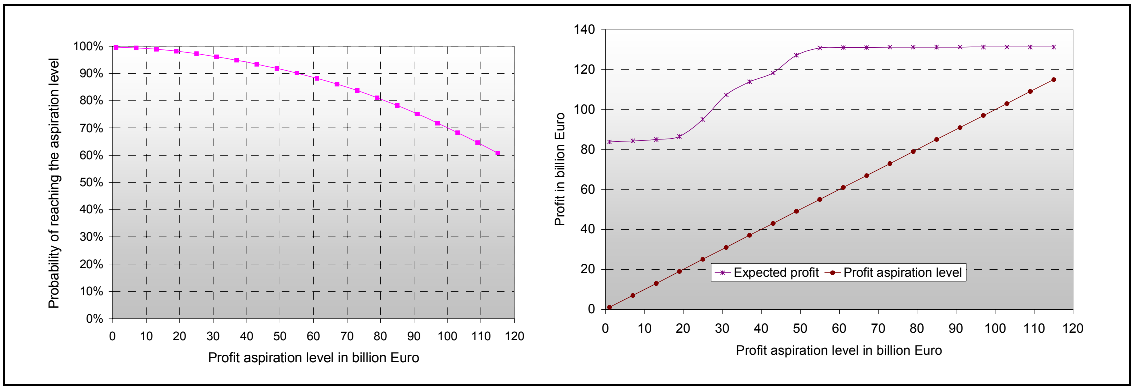
3.3. Series of ISPA Runs (Sensitivity Analysis)

In general terms, a sensitivity analysis consists of additional model runs, in which input parameters are changed systematically. The resulting changes of model outputs are then analyzed in their dependence of the varying inputs.

As a first question about the sensitivity of base-case results, we look at our main objective and investigate how increasing our aspiration level in terms of profitability changes the expected profitability, what changes this implies for the side objectives, and how this influences our optimal R&D strategy. As a methodological side remark, we note here that one straightforward question has answers in many parts of the model, which is indicative of the multitude of tasks that can be undertaken with ISPA.

Our sensitivity analysis consisted of a series of model runs in which we increased the profitability threshold in 20 steps between 1 and 115 billion euros. Let us first investigate how these increasing aspirations influence the probability of achieving them and how they influence the expected profitability. The answer to this question is given in Figure 3-4 .

Figure 3-4 Probability of meeting increasing aspirations with respect to profitability and expected profitability.



In the left part of the figure, we find the expected result that increasing aspiration levels are accompanied by decreasing probabilities of achieving them. More interesting is the result

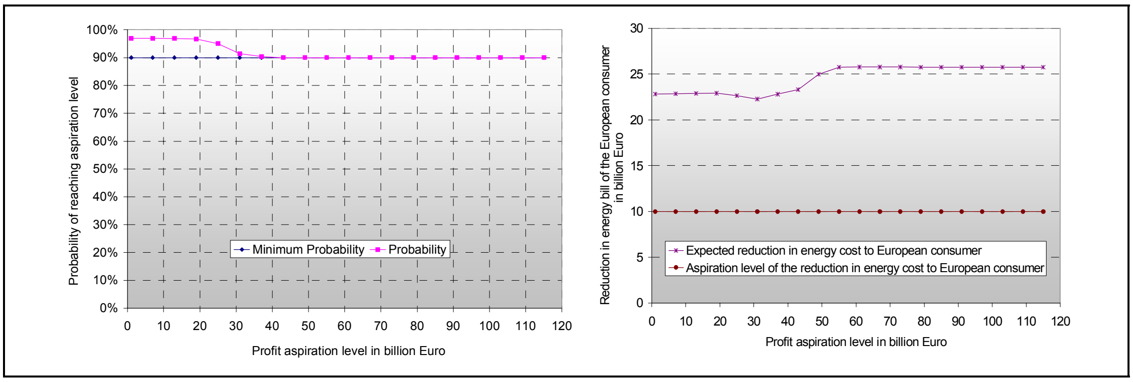
---

[48] One percentage point "costs" roughly € 70 million (1 billion, divided by 14). One hundredth of a percentage point therefore "costs" € 700,000.

displayed on the right side of the figure, which shows the expected profitability as a function of the aspired profitability. We find that the expected profitability remains near 80 billion euros for increasing but low aspirations. Only if aspirations rise above 25 billion, so does the expected profitability. This effect has a limit near a profitability level of 130 billion euros, above which the expected profitability does not increase further – whatever the aspiration levels.

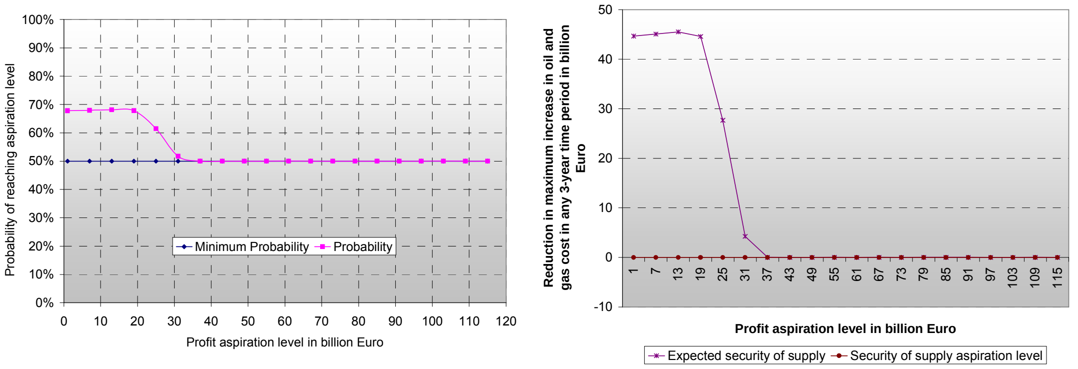
From this picture, we conclude that there must be some sort of compensatory price to be paid for the expected profitability to increase from 80 to 130 billion. Recall that in the base case, there was some "slack" in the system, which led to some "over-performance" with respect to side objectives. These side objectives, energy cost to the European consumer and security of supply, therefore suggest themselves as the first places where to look for changes with respect to the base case. The results of these two pieces of sensitivity analysis are shown in Figure 3-5 and Figure 3-6 .

Figure 3-5 Probability of exceeding aspiration level for the reduction in energy cost (left) and expected impact of R&D budget allocation on the reduction in energy cost to European consumer (right).



The two figures confirm that increased expected profitability is "bought" by decreasing probabilities of meeting the two side objectives energy cost savings to the European consumer and security of supply. For the latter, decreasing probabilities are also accompanied by a complete loss of supply security in terms of the chosen indicator. The results with respect to energy cost to the European consumer show a different kind of variability: First, expected cost savings fall in tandem with the probability but later, they rise again. Taken the results of these two figures together illustrates the potential of cost savings in the absence of supply security.

Figure 3-6 Probability of exceeding aspiration level for the security of supply (left) and expected impact of R&D budget allocation on the security of supply (right).



The two figures confirm that increased expected profitability is "bought" by decreasing probabilities of meeting the two side objectives energy cost savings to the European consumer and security of supply. For the latter, decreasing probabilities are also accompanied by a complete loss of supply security in terms of the chosen indicator. The results with respect to energy cost to the European consumer show a different kind of variability: First, expected cost savings fall in

tandem with the probability but later, they rise again. Taken the results of these two figures together illustrates the potential of cost savings in the absence of supply security.

Figure 3-7 Probability of exceeding aspiration level (left) and expected impact of R&D budget allocation on cumulative CO_2 reduction (right).

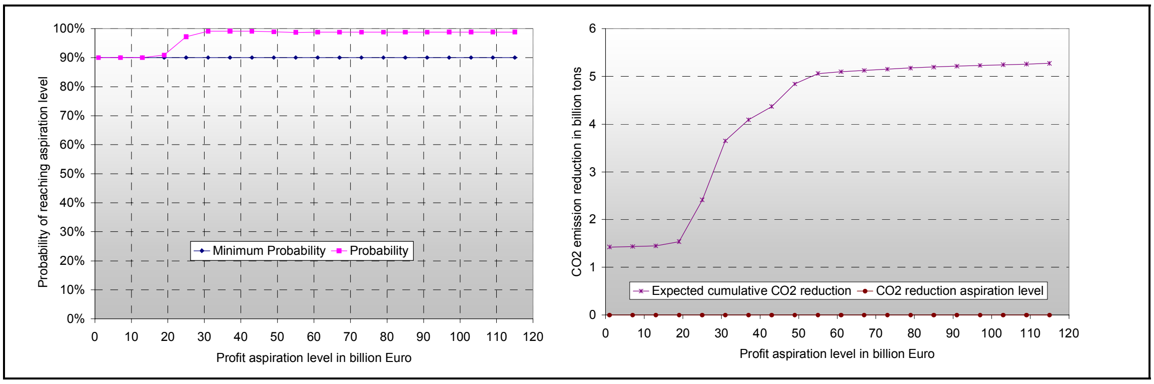
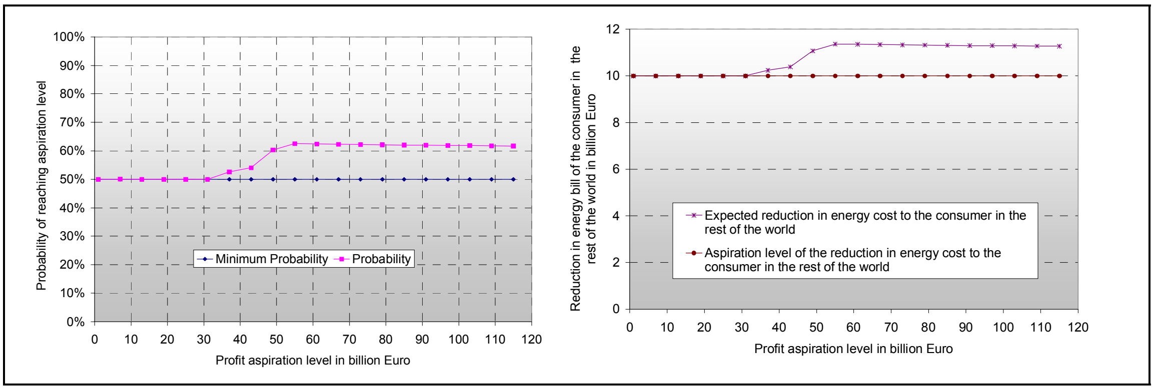


Figure 3-8 Probability of exceeding aspiration level (left) and expected impact of R&D budget allocation on energy cost savings to the consumer in the rest of the world (right).

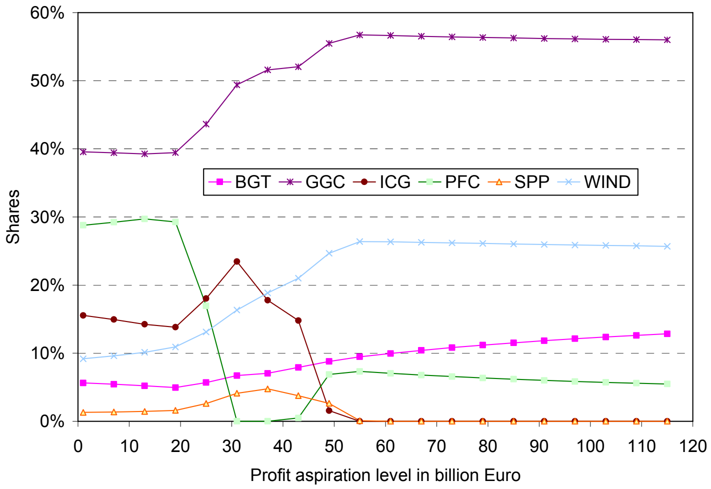


Taken together, the results of the sensitivity analysis on all objectives show that in ISPA, security of supply is the most powerful side objective in the sense that all other side objectives are allowed to “thrive” at the expense of supply security.

Let us try to understand these results of the sensitivity analysis by looking how the allocation of R&D budget on the energy conversion technologies changes in the course of the sensitivity analysis.

When increasing the aspiration level for the profitability objective, the number of supported technologies drops to four, as Integrated Coal Gasification (ICG) and Solar Thermal Power (SPP) technologies receive no R&D support for profit aspiration levels exceeding 55 billion euros. The remaining four technologies – Biomass Gasification Gas Turbine (BGT), Gas Turbine Combined Cycle (GGC), Super-critical Coal (PFC), and Wind Turbines (WIND) – are characterized by particularly high expected profitability and also by high variances, which create the possibility of high profits.

Figure 3-9 Varying the base case of ISPA. Optimal R&D budget shares (only technologies with non-zero support are shown); profitability aspiration thresholds vary between 1 and 115 billion.



3.4. Risks and Trade-offs

All we changed for the sensitivity analysis described in the previous section was the aspiration level for the main objective, profitability. Watching the developments of the impacts of R&D spending on the side objectives, we left their aspiration levels and minimum probabilities unchanged. Remembering the definition of risk as used here – "probability of an undesired outcome" – we now continue our sensitivity analysis by giving an example of using ISPA for risk analysis. We shall do so by illustrating that reducing the risk of supply problems, i.e., specifying higher aspiration probabilities for one objective ("security of supply"), the probabilities of achieving the other objectives' aspiration levels decrease – which means increasing risks.

Figure 3-10 shows how the probabilities of the other four objectives (including one main objective – "TPROFIT" – and three other side objectives) change as we increase the aspiration probability for the "security of supply" (TSECURE).

The figure demonstrates that with the aspiration probability for security of supply (TSECURE) moving from 0.4 to 0.725, the probability of achieving the main objective (TPROFIT at least 100 billion, see footnote 49 decreases from 0.71 to 0.53. In other words, the risk of not meeting the aspiration level for the objective TPROFIT gets higher accordingly. Another objective that decreases its probability of achieving the aspiration level quite significantly is "change in energy cost in ROW" (TEC3). The probability of achieving at least no increase of energy cost outside Europe decreases from 0.67 to 0.5 (0.5 is the aspiration probability), and the according constraint becomes binding. The probability for "Cumulative CO_2 Emission Change" remaining below zero (TCO_2) decreases from 0.99 to 0.9 (0.9 is aspiration probability).

Figure 3-10 Development of probability of the other objectives with increasing aspiration probability for the security of supply[49].

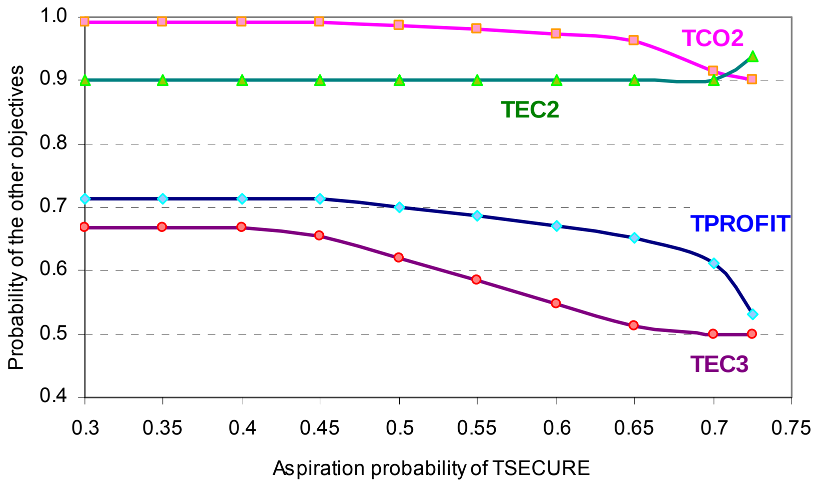
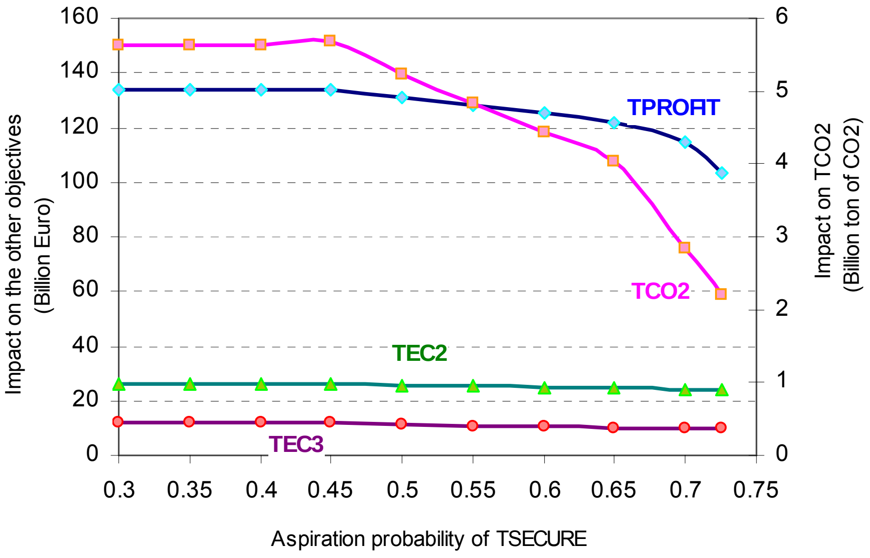


Figure 3-11 shows how the *expected impacts* on the objectives change as we increase the aspiration probability for "security of supply" (TSECURE). As the figure shows, all other objectives' expected impact decreases when aspiration probability for the TSECURE is set higher[50].

Figure 3-11 Development of impact on the objectives with increasing aspiration probability for the security of supply.



The figure also illustrates that – as the aspiration probability for security of supply (TSECURE) increases from 0.4 to 0.725 – the expected impact on the main objective (TPROFIT) decreases

---

[49] In the range of the aspiration probability of TSECURE between 0.3 and 0.4, probabilities for all the other objectives remain constant. This is because probability for achieving the aspiration level (which is set at 0) for TSECURE is 0.44 and when we set the aspiration probability of TSECURE below 0.44, this constraint does not constrain the results. Similarly, the figure does not show the value for 0.75 and above, because aspiration levels higher than 0.75 become too strict that the computation of the optimal allocation of the R&D becomes "infeasible". Note that – for demonstration purposes – the aspiration level of the main objective is set at 100, instead of 10 in the reference case. The reason is that with 10, the ranges of aspiration level that gives change in the probabilities of the other aspiration level was very limited (0.68 was the binding level and 0.75 already gives infeasible results when the main objective threshold is set at 10).

[50] Note that the expected impact for TSECURE increases with higher aspiration probability.

from 134 billion Euros to 103 billion Euros. Expected impacts on energy cost reductions to the consumer also decrease from 26 billion Euro to 24 billion Euro in the case of TEC2 (consumers in Europe) and from 12 billion Euro to 10 billion Euro in the case of TEC3 (consumers in the rest of the world). The impact on cumulative CO_2 emissions changes also from 5.6 to 2.8 billion ton reduction of CO_2 emissions.

4. Interactive Use of ISPA with the ISPA Excel Tool

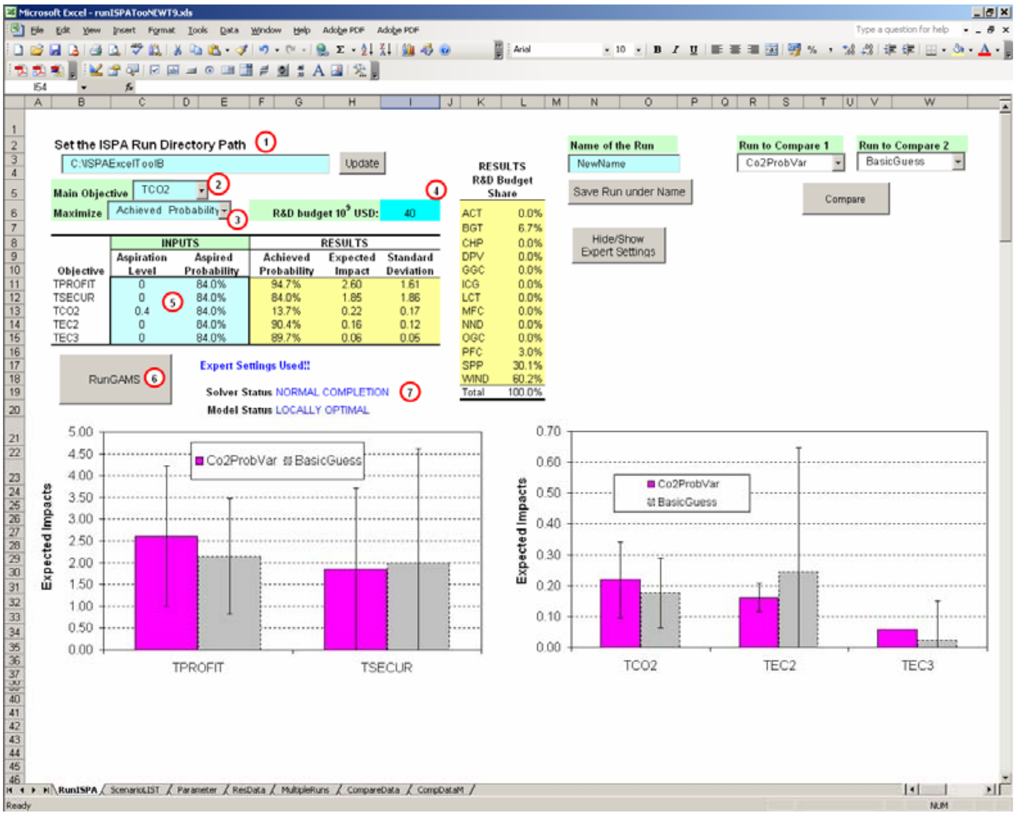
4.1. Installation Guide

For this section, the latest ISPA version (at the time of writing) shows non-linear impacts of the total R&D budget. This differs from Section 2 where a linear version of ISPA is used in the examples.

In order to run the Excel tool, a user must extract the supplied files and copy them into one folder. GAMS must be installed and usable from this folder.

To use the user interface, the user simply opens the "runISPA.xls" file. The main Excel user interface is depicted below in Figure 4-1.

Figure 4-1: The main window of the Excel Tool for ISPA use.



Set the ISPA Run Directory Path ①
C:\ISPAExcelToolB

Main Objective: TCO2 ②
Maximize: Achieved Probability ③
R&D budget 10^9 USD: 40 ④

	INPUTS		RESULTS		
Objective	Aspiration Level	Aspired Probability	Achieved Probability	Expected Impact	Standard Deviation
TPROFIT	0	84.0%	94.7%	2.60	1.61
TSECUR	0	84.0%	84.0%	1.85	1.86
TCO2	0.4	84.0%	13.7%	0.22	0.17
TEC2	0	84.0%	90.4%	0.16	0.12
TEC3	0	84.0%	89.7%	0.06	0.05

⑤ ⑥

Expert Settings Used!!

Solver Status NORMAL COMPLETION ⑦
Model Status LOCALLY OPTIMAL

RESULTS R&D Budget Share	
ACT	0.0%
BGT	6.7%
CHP	0.0%
DPV	0.0%
GGC	0.0%
ICG	0.0%
LCT	0.0%
MFC	0.0%
NND	0.0%
OGC	0.0%
PFC	3.0%
SPP	30.1%
WIND	60.2%
Total	100.0%

Name of the Run: NewName
Run to Compare 1: Co2ProbVar
Run to Compare 2: BasicGuess

The six steps required to run an ISPA case are highlighted in the Excel file by numbered red circles. The first step is to enter the path of the ISPA folder into the text box "Set the ISPA Run Directory Path" (1) and to press the "update" button. Then select the main objective (2) and select either to maximize the probability of reaching the given aspiration level or the expectation value of the main objective (3). Set the R&D budget (4). Then enter the side objective aspiration levels and the required probabilities (5). Then hit the "RunGAMS" button (6) and watch the results being displayed after a few seconds. It is important to check the solver and model status: If there is an infeasibility or non-optimal solution, it will be reported at point (7).

The aspiration levels (inputs) and expected impacts (outputs) are given in units per billion USD of total R&D!! This removes dominant linear response of the expected impact per R&D budget and makes the budgetary efficiency aspects transparent. E.g. does the expected impact per R&D budget increase or decrease with the targeted budget?

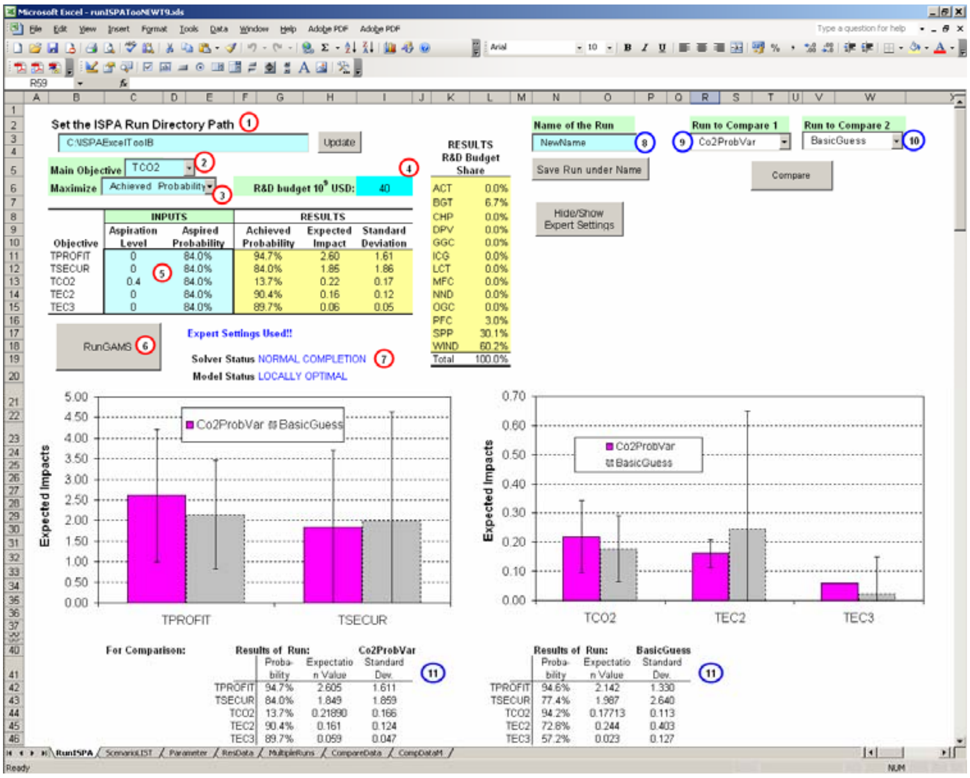
All the entry fields have a light-blue background color, and the cells with the results have a yellow background color. The result of the run for the five objectives is depicted in two bar charts. The columns depict the expectation value and the error bars give the standard deviation. The yellow fields display the numerical values and the R&D budget allocation. To use the Excel tool the user needs only the "runISPA" and "ScenarioLIST" sheet. The other Excel sheets are used only by the Visual Basic code to store data and to do calculations.

4.2. Helpful Features

To save a specific run, for instance, to be able to compare this run later with other runs, just enter a name into the field (8) where *"NewName"* is displayed and hit the *"Save Run under Name"* button. In order to compare the different results, select two different runs in the drop down lists (9) and (10) and then press the *"Compare"* button. The results of the two runs are displayed in the two graphs. Again the colons depict the expectation value and the error bars depict the standard deviation. The numerical results of the runs are displayed in two tables below the graphs see (11).

For the selected "*Run to Compare 1*", the input fields for the GAMS run (underlined blue) are reloaded as they were defined for this run. To remove a run from the list of saved runs or to rearrange the list, switch to the "*ScenarioList*" Excel sheet and delete or reorder entries there.

Figure 4-2: The "save" and "compare runs" features (circles 7-10).



Set the ISPA Run Directory Path ① C:\ISPAExcelToolB

Main Objective TCO2

Maximize Achieved Probability

R&D budget 10^9 USD: 40

	INPUTS		RESULTS		
Objective	Aspiration Level	Aspired Probability	Achieved Probability	Expected Impact	Standard Deviation
TPROFIT	0	84.0%	94.7%	2.60	1.61
TSECUR	0	84.0%	84.0%	1.85	1.86
TCO2	0.4	84.0%	13.7%	0.22	0.17
TEC2	0	84.0%	90.4%	0.16	0.12
TEC3	0	84.0%	89.7%	0.06	0.05

RESULTS R&D Budget Share	
ACT	0.0%
BGT	6.7%
CHP	0.0%
DPV	0.0%
GGC	0.0%
ICG	0.0%
LCT	0.0%
MFC	0.0%
NND	0.0%
OGC	0.0%
PFC	3.0%
SPP	30.1%
WIND	60.2%
Total	100.0%

Expert Settings Used!!

Solver Status NORMAL COMPLETION

Model Status LOCALLY OPTIMAL

Name of the Run: NewName

Run to Compare 1: Co2ProbVar

Run to Compare 2: BasicGuess

For Comparison:

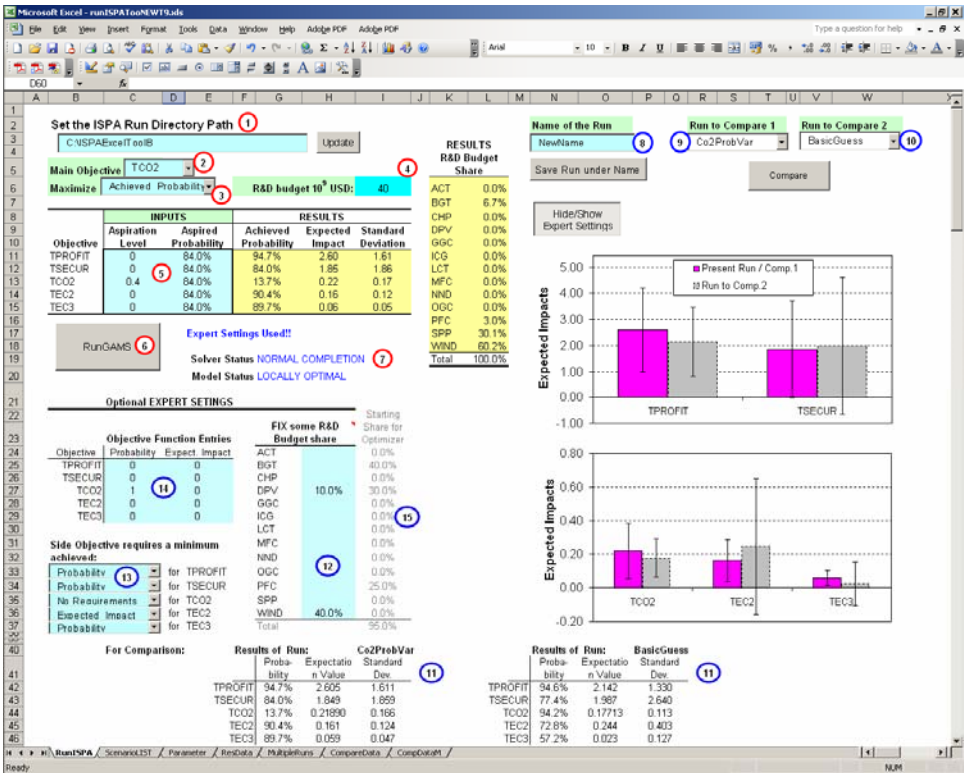
Results of Run: Co2ProbVar	Probability	Expectation Value	Standard Dev.
TPROFIT	94.7%	2.605	1.611
TSECUR	84.0%	1.849	1.859
TCO2	13.7%	0.21890	0.166
TEC2	90.4%	0.161	0.124
TEC3	89.7%	0.059	0.047

Results of Run: BasicGuess	Probability	Expectation Value	Standard Dev.
TPROFIT	94.6%	2.142	1.330
TSECUR	77.4%	1.987	2.640
TCO2	94.2%	0.17713	0.113
TEC2	72.8%	0.244	0.403
TEC3	57.2%	0.023	0.127

4.3. Advanced Settings

If users have more precise requirements for the optimization they can use the so-called expert options. For this purpose press the *"Hide/Show Expert Settings"* toggle button. After pressing, the Excel window will then look like depicted as follows:

Figure 4-3 The expert settings (circles 12-14).



Set the ISPA Run Directory Path: C:\ISPAExcelToolB

Main Objective: TCO2

Maximize: Achieved Probability

R&D budget 10^9 USD: 40

	INPUTS		RESULTS		
Objective	Aspiration Level	Aspired Probability	Achieved Probability	Expected Impact	Standard Deviation
TPROFIT	0	84.0%	94.7%	2.60	1.61
TSECUR	0	84.0%	84.0%	1.85	1.86
TCO2	0.4	84.0%	13.7%	0.22	0.17
TEC2	0	84.0%	90.4%	0.16	0.12
TEC3	0	84.0%	89.7%	0.06	0.05

Expert Settings Used!!

Solver Status NORMAL COMPLETION

Model Status LOCALLY OPTIMAL

RESULTS R&D Budget Share	
ACT	0.0%
BGT	6.7%
CHP	0.0%
DPV	0.0%
GGC	0.0%
ICG	0.0%
LCT	0.0%
MFC	0.0%
NND	0.0%
OGC	0.0%
PFC	3.0%
SPP	30.1%
WIND	60.2%
Total	100.0%

Name of the Run: NewName

Run to Compare 1: Co2ProbVar

Run to Compare 2: BasicGuess

Optional EXPERT SETINGS

Objective	Objective Function Entries: Probability	Expect. Impact
TPROFIT	0	0
TSECUR	0	0
TCO2	1	0
TEC2	0	0
TEC3	0	0

	FIX some R&D Budget share	Starting Share for Optimizer
ACT		0.0%
BGT		40.0%
CHP		0.0%
DPV	10.0%	30.0%
GGC		0.0%
ICG		0.0%
LCT		0.0%
MFC		0.0%
NND		0.0%
OGC		0.0%
PFC		25.0%
SPP		0.0%
WIND	40.0%	0.0%
Total		95.0%

Side Objective requires a minimum achieved:

Probability for TPROFIT
Probability for TSECUR
No Requirements for TCO2
Expected Impact for TEC2
Probability for TEC3

For Comparison:

Results of Run: Co2ProbVar	Probability	Expectation Value	Standard Dev.
TPROFIT	94.7%	2.605	1.611
TSECUR	84.0%	1.849	1.859
TCO2	13.7%	0.21890	0.166
TEC2	90.4%	0.161	0.124
TEC3	89.7%	0.059	0.047

Results of Run: BasicGuess	Probability	Expectation Value	Standard Dev.
TPROFIT	94.6%	2.142	1.330
TSECUR	77.4%	1.987	2.640
TCO2	94.2%	0.17713	0.113
TEC2	72.8%	0.244	0.403
TEC3	57.2%	0.023	0.127

Using the expert settings, the following functions can be performed

(1) Fix the R&D budget:

In the case users want to devote a fixed part of the R&D budget to a certain technology and leave the rest up to optimization, they can do this by entering values in (12). If there is no entry, then R&D support of this technology will be optimized. If a number is entered for a certain technology, then R&D share spent on this technology will be fixed at this value. In Figure 4-3, DPV and WIND are given a fixed share for the next run.

(2) The side objectives:

For each side objective, users can specify (13) whether the side objective is defined by prescribing probabilities of aspiration levels, by minimum expectation values or whether no limits are imposed on this side objective. In the case the side objective is defined as a minimum expectation value, the aspiration level entered in (5) is used as the minimum required level for the expected impact of this objective. In this case, the probability entered in (5) has no meaning

(3) The "weighted objective" optimization:

In the standard settings of the Excel tool, the objective function is defined using the settings in (2) and (3) so as to maximize the aspiration probability or the expectation value of one (main) objective. Here, with the expert settings, users can define the objective function so as to maximize a weighted sum of all objectives. Users can specify the 2x5 matrix (14), which determines the objective function directly, by entering any numbers. Using settings (2) and (3) just simplifies the definition of the matrix (11). The 2x5 matrix (11) determines how the aspiration probability or/and expectation value of which objective is weighted in the objective function.

(4) The multiple-run parameter variation:

It is possible to make multiple ISPA runs with the ISPA Excel Tool and display the results. Parameters which can be (simultaneously) varied are the total R&D Budget and the threshold (plus its required probability) for one selected objective (see Figure 4-4).

The impact of R&D spending is not linear with the total available budget. To study this effect, the total R&D budget can be varied by setting a starting value and an increment in the expert settings.

It is also possible to leave the budget constant and to vary only the threshold and required probability for a certain objective. This is possible regardless of whether this objective is the main objective or not. The settings for the multiple runs do not change the effect of any other settings besides the total R&D budget and the aspiration level and aspired probability of a selected objective.

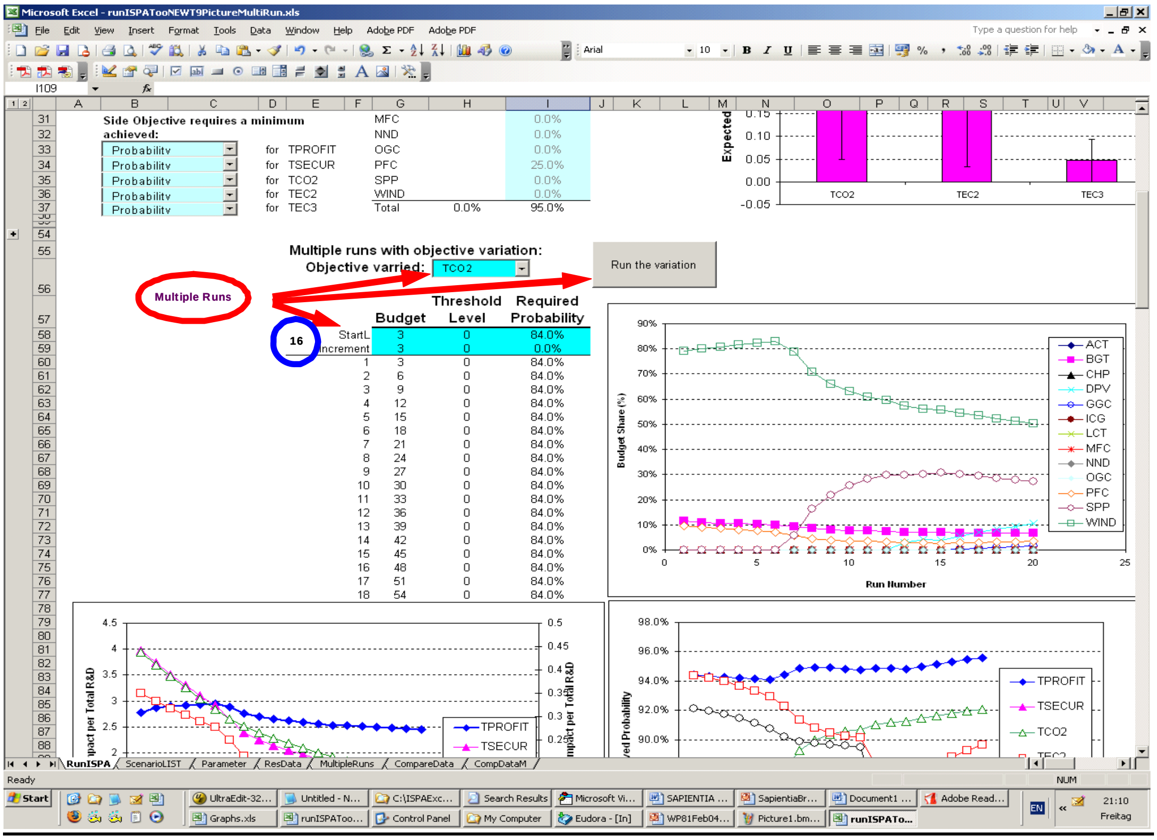
An example of a budget variation is shown in Figure 4-4 and Figure 4-5. It is assumed that the ISPA Excel Tool maximizes the expected impact of the TCO$_2$ objective while no objective should deteriorate with at least 84% probability, i.e., to remain within one standard deviation above zero. And this assumptions the total R&D budget is varied from 0 to 60 billion USD.

The results of the variation are shown in Figure 4-5. The results of the expected impact are given in impact per billion USD. So if the impact would be linear with the R&D budget then the results should be a horizontal line. For the expected impact, the results the TPROFIT and TSECUR relate to the left axis and TCO$_2$, TEC2 and TEC3 relate to the right axis of Figure 4-5.

<u>Trouble shooting:</u>

Using the setting (15) (see Figure 4-3) users can enter a starting level for the optimizer. There is no need to change these values, except in cases where the optimizer has difficulties finding the optimal solution. Then a different starting point may help. Similarly, the solver sometimes displays an error if aspiration levels are set to 0. A way around this difficulty is to introduce aspiration levels larger than 0 that can be expected to be non-binding. Such values do not influence the optimization results, but permit the software's algorithms to obtain a solution. These are problems of the solver and not of the Excel tool.

<u>Figure 4-4 : How to make multiple runs with the ISPA Excel Tool.</u>



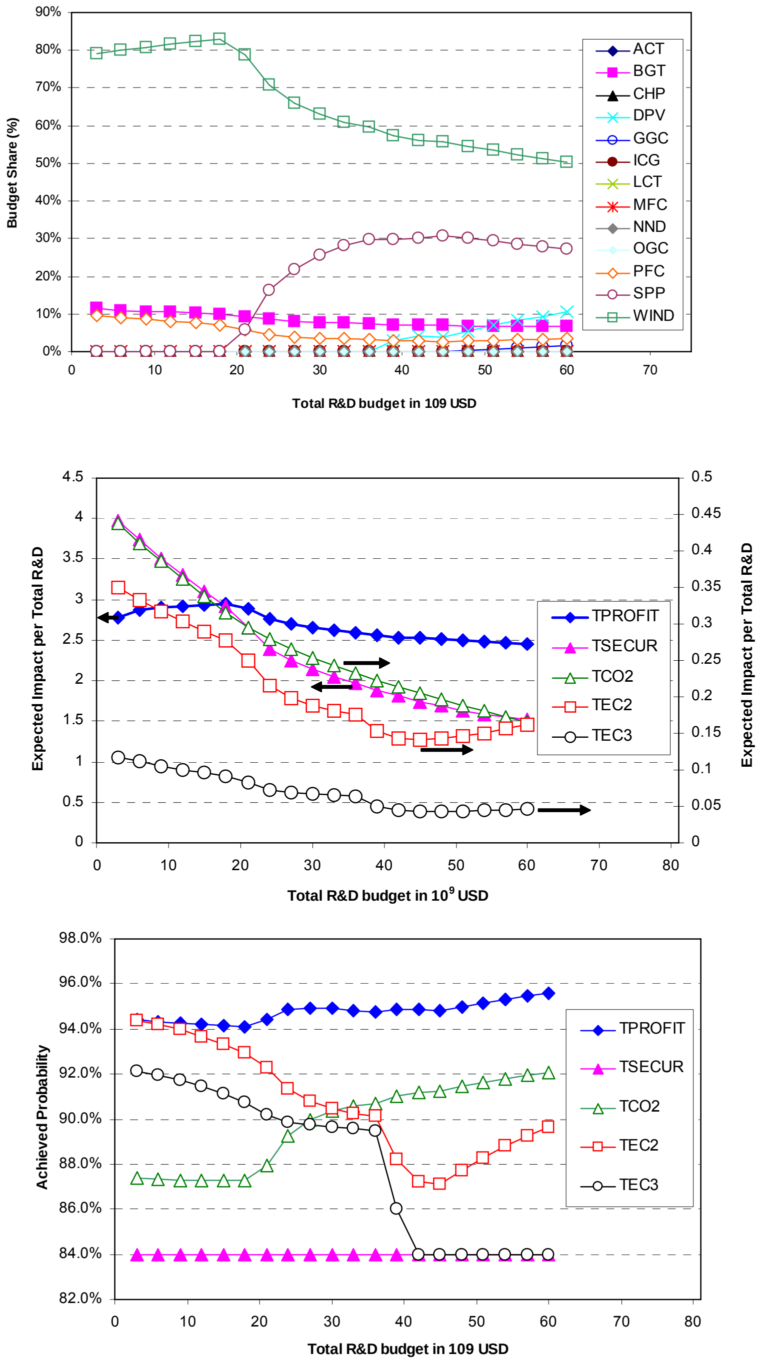
Side Objective requires a minimum achieved:

Probability	for TPROFIT	MFC		0.0%
Probability	for TSECUR	NND		0.0%
Probability	for TCO2	OGC		0.0%
Probability	for TEC2	PFC		25.0%
Probability	for TEC3	SPP		0.0%
		WIND		0.0%
		Total	0.0%	95.0%

Multiple runs with objective variation:
Objective varried: TCO2

	Budget	Threshold Level	Required Probability
StartL	3	0	84.0%
Increment	3	0	0.0%
1	3	0	84.0%
2	6	0	84.0%
3	9	0	84.0%
4	12	0	84.0%
5	15	0	84.0%
6	18	0	84.0%
7	21	0	84.0%
8	24	0	84.0%
9	27	0	84.0%
10	30	0	84.0%
11	33	0	84.0%
12	36	0	84.0%
13	39	0	84.0%
14	42	0	84.0%
15	45	0	84.0%
16	48	0	84.0%
17	51	0	84.0%
18	54	0	84.0%

Figure 4-5: Results of the budget variation.



4.4. Exploring ISPA with the ISPA Excel Tool

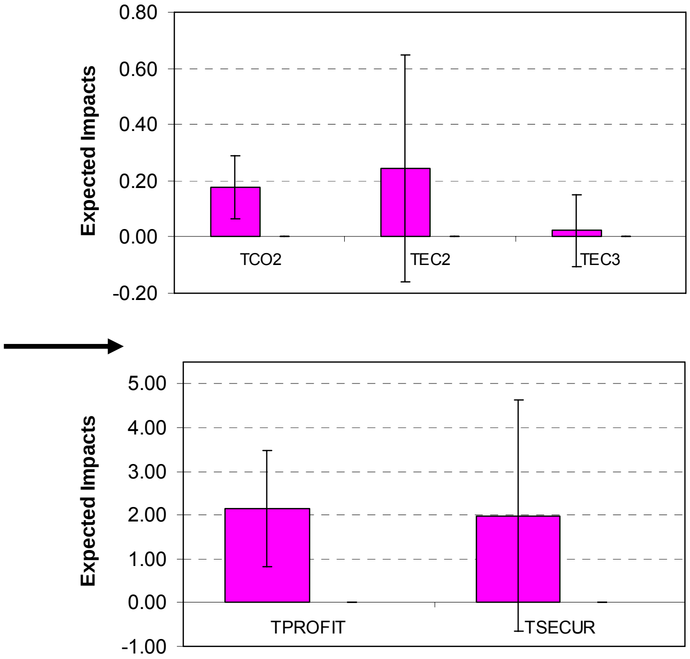
Let us assume a hypothetical analysis in which the goals are:

- To reduce CO_2 emissions.
- No objective should deteriorate with at least 84% probability, i.e., within one standard deviation.

(1) The first attempt (guess) is to spend R&D support evenly on four renewable technologies (see below). For further reference, we call this run the *Best Manual Guess* run. The result is shown in the graphs below.

Figure 4-6 Results for the Best Manual Guess run. The ISPA Excel Tool shows the results above, but ISPA has nothing to optimize in this run, since the entire R&D budget shares were manually fixed (see setting (12) in Figure 4-3).

R&D Budget Share	
ACT	0.0%
BGT	25.0%
CHP	0.0%
DPV	25.0%
GGC	0.0%
ICG	0.0%
LCT	0.0%
MFC	0.0%
NND	0.0%
OGC	0.0%
PFC	0.0%
SPP	25.0%
WIND	25.0%
Total	100.0%

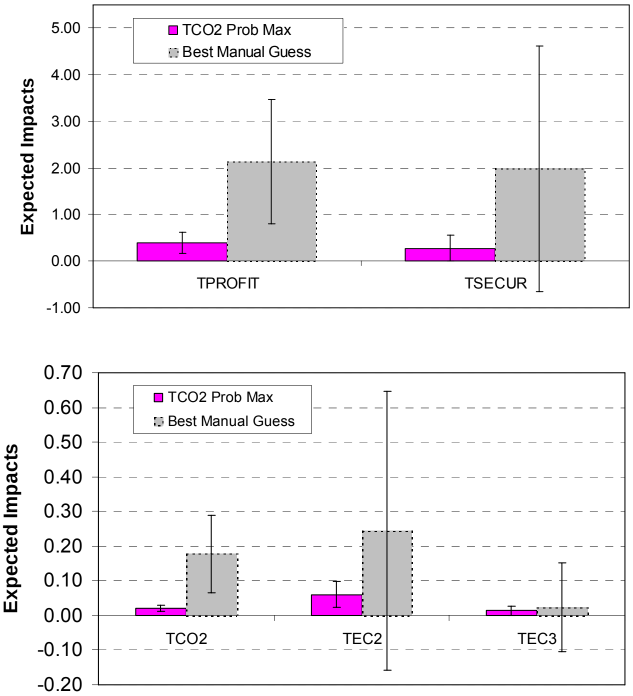


We can also see that the error bars go below 0 for four objectives. So the manual guess does not achieve the “no objective should deteriorate within one standard deviation” criterion.

(2) Second attempt: use the ISPA Excel Tool to maximize the probability of the TCO_2 objective (see setting (3) in Figure 4-3) while no objective should deteriorate with at least 84% probability. This gives the following results:

Figure 4-7 Results of ISPA maximizing the probability of the TCO_2 objective. The result is given in pink color. The gray bars are the result of the previous Best Manual Guess run.

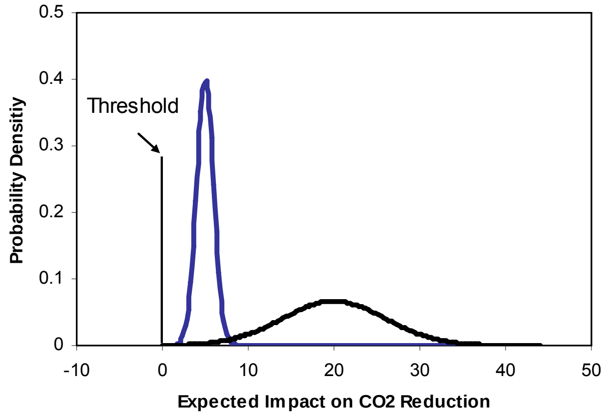
RESULTS R&D Budget Share	
ACT	3.4%
BGT	0.8%
CHP	0.0%
DPV	3.3%
GGC	0.8%
ICG	0.5%
LCT	0.0%
MFC	0.0%
NND	88.0%
OGC	0.0%
PFC	0.3%
SPP	1.7%
WIND	1.2%
Total	100.0%



Why does the result for the Best Manual Guess run seem to be better – in terms of the expected impact for the TCO_2 objective – than the ISPA optimization run? The reason is that the probability of the TCO_2 objective was maximized. The optimized R&D budget spending results in a very narrow distribution for the TCO_2 objective. The probability for the TCO_2 objective to be larger than zero is indeed 99.3% and higher as in the Best Manual Guess run (94%): i.e. the optimization ensures with very high probability a small impact.

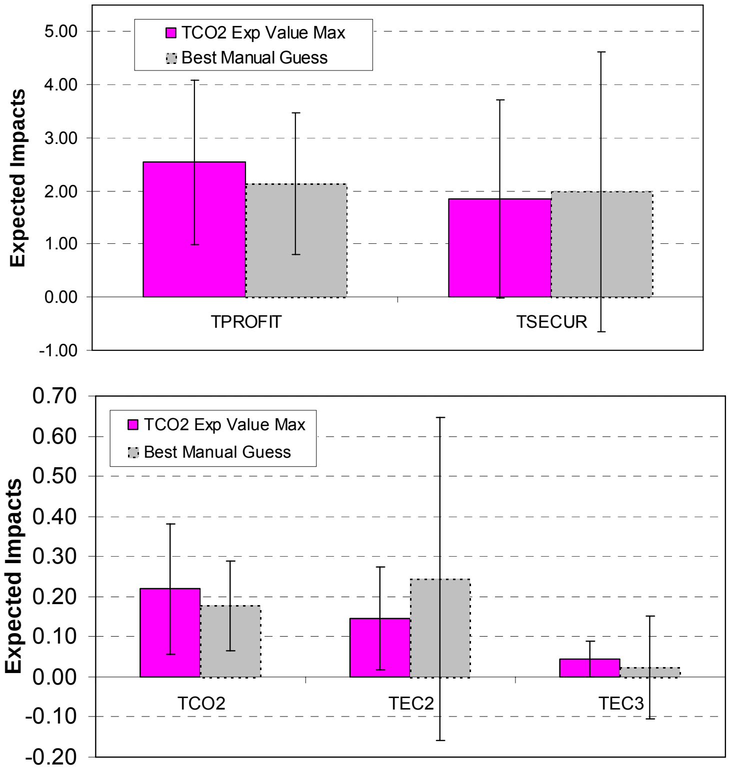
Figure 22 illustrates how a very narrow but low impact distribution can have a higher probability to be above a certain threshold than a high impact but broad distribution.

Figure 4-8 If the distribution with the lower expected impact (depicted blue) is narrow enough then the probability to have some positive CO_2 reduction impact is higher for the blue distribution than for the black distribution



(3) Third attempt: use the ISPA Excel Tool to maximize the expected impact of the TCO_2 objective (see setting (3) in Figure 4-3) while no objective should deteriorate with at least 84% probability.

Figure 4-9 Optimizing the R&D spending to achieve a high expected CO_2 reduction.



The results show that with this setting one achieves the highest expected CO_2 reduction with still high probability (91%).

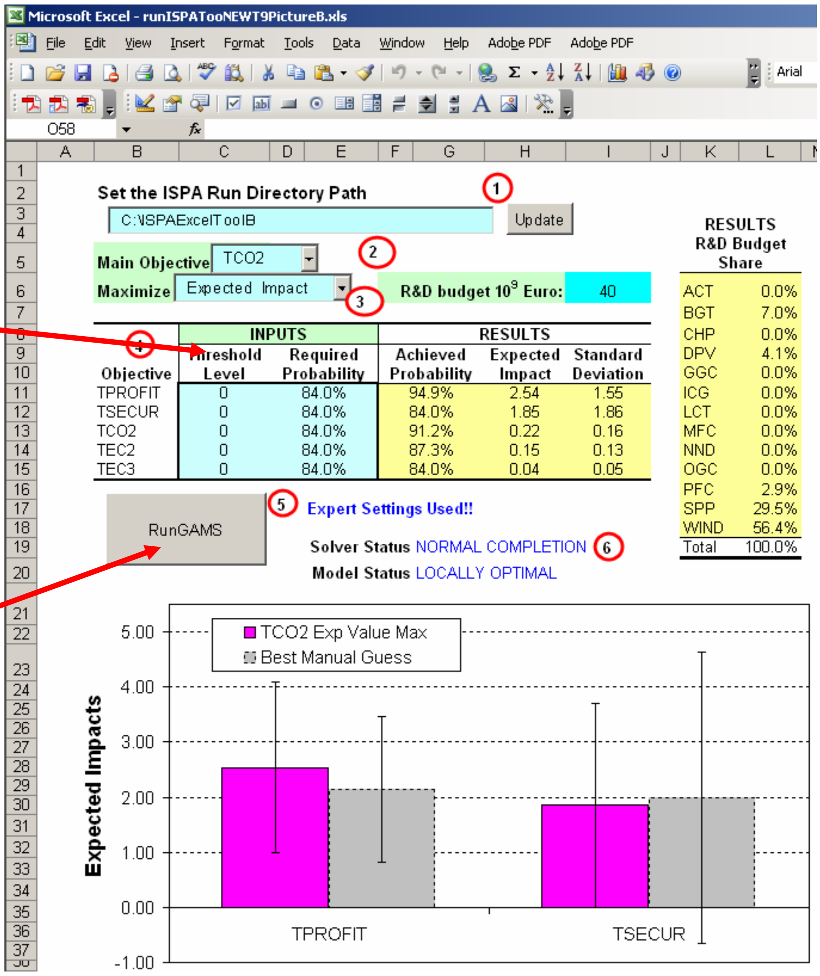
4.5. Suggestions for the use of the ISPA Excel Tool

We therefore suggest the following for using ISPA:

1) To define the main objective as maximizing the expected impact of the most important, i.e., the main objective.

2) Set the required minimum threshold levels and probabilities for all objectives and to specify the side constraints by probability values.

3) Maybe run a budget variation to see the budget effects.



Set the ISPA Run Directory Path
C:\ISPAExcelToolB

Main Objective: TCO2

Maximize: Expected Impact

R&D budget 10^9 Euro: 40

	INPUTS		RESULTS		
Objective	Threshold Level	Required Probability	Achieved Probability	Expected Impact	Standard Deviation
TPROFIT	0	84.0%	94.9%	2.54	1.55
TSECUR	0	84.0%	84.0%	1.85	1.86
TCO2	0	84.0%	91.2%	0.22	0.16
TEC2	0	84.0%	87.3%	0.15	0.13
TEC3	0	84.0%	84.0%	0.04	0.05

Expert Settings Used!!

Solver Status NORMAL COMPLETION

Model Status LOCALLY OPTIMAL

RESULTS R&D Budget Share	
ACT	0.0%
BGT	7.0%
CHP	0.0%
DPV	4.1%
GGC	0.0%
ICG	0.0%
LCT	0.0%
MFC	0.0%
NND	0.0%
OGC	0.0%
PFC	2.9%
SPP	29.5%
WIND	56.4%
Total	100.0%

An alternative method would be to use the expert settings to maximize a weighted mix of expected impacts of the most important objectives (see the expert settings section).

References

De Finetti, B., 1974, *Theory of Probability*, John Wiley & Sons, London, New York, Sydney, Toronto.

Kouvaritakis, N., 2002, “A More Concrete Specification of the ISPA meta-Model”, mimeo.

APPENDIX: In this appendix, we document the five variance-covariance matrices of the linear ISPA version.

Table 4-1 Variance-covariance matrices for each objective. The diagonal elements (italics) are the variances.

TPROFIT	ACT	BGT	CHP	DPV	GGC	ICG	LCT	MFC	NND	OGC	PFC	SPP	WIND
ACT	*0.01*	-0.02	0.00	-0.02	-0.03	0.01	0.00	0.01	0.00	0.00	0.01	-0.01	-0.04
BGT	-0.02	*144.52*	1.24	2.58	-4.94	-2.06	-0.13	4.55	-0.03	-1.01	-1.05	2.82	63.20
CHP	0.00	1.24	*0.68*	0.24	-0.42	0.01	0.00	0.49	0.00	-0.01	-0.07	0.46	0.59
DPV	-0.02	2.58	0.24	*15.79*	-1.54	-0.04	-0.03	-0.17	0.00	0.01	-0.51	6.48	11.19
GGC	-0.03	-4.94	-0.42	-1.54	*42.77*	-0.65	0.00	-1.95	0.00	0.24	0.05	-1.32	-9.73
ICG	0.01	-2.06	0.01	-0.04	-0.65	*8.12*	0.07	-0.51	0.00	0.04	1.20	1.08	-1.62
LCT	0.00	-0.13	0.00	-0.03	0.00	0.07	*0.05*	0.00	0.00	0.02	0.03	0.05	0.12
MFC	0.01	4.55	0.49	-0.17	-1.95	-0.51	0.00	*24.34*	0.00	0.03	0.38	0.37	2.11
NND	0.00	-0.03	0.00	0.00	0.00	0.00	0.00	0.00	*0.00*	0.00	0.00	0.00	-0.06
OGC	0.00	-1.01	-0.01	0.01	0.24	0.04	0.02	0.03	0.00	*0.94*	0.04	0.56	-1.13
PFC	0.01	-1.05	-0.07	-0.51	0.05	1.20	0.03	0.38	0.00	0.04	*4.22*	-0.07	-2.46
SPP	-0.01	2.82	0.46	6.48	-1.32	1.08	0.05	0.37	0.00	0.56	-0.07	*117.41*	20.23
WIND	-0.04	63.20	0.59	11.19	-9.73	-1.62	0.12	2.11	-0.06	-1.13	-2.46	20.23	*285.87*

TCO$_2$	ACT	BGT	CHP	DPV	GGC	ICG	LCT	MFC	NND	OGC	PFC	SPP	WIND
ACT	*0.00*	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01
BGT	0.00	*0.78*	-0.02	-0.01	-0.05	-0.02	0.00	0.00	0.00	0.02	-0.04	-0.01	0.06
CHP	0.00	-0.02	*0.00*	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.01
DPV	0.00	-0.01	0.00	*0.01*	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GGC	0.00	-0.05	0.00	0.00	*0.06*	0.00	0.00	0.00	0.00	-0.01	0.00	0.00	-0.04
ICG	0.00	-0.02	0.00	0.00	0.00	*0.01*	0.00	0.00	0.00	0.00	0.01	0.00	-0.03
LCT	0.00	0.00	0.00	0.00	0.00	0.00	*0.00*	0.00	0.00	0.00	0.00	0.00	0.00
MFC	0.00	0.00	0.00	0.00	0.00	0.00	0.00	*0.02*	0.00	0.00	0.00	0.00	-0.01
NND	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	*0.00*	0.00	0.00	0.00	0.00
OGC	0.00	0.02	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	*0.03*	0.00	0.00	0.01
PFC	0.00	-0.04	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	*0.04*	0.00	-0.04
SPP	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	*0.05*	0.00
WIND	-0.01	0.06	-0.01	0.00	-0.04	-0.03	0.00	-0.01	0.00	0.01	-0.04	0.00	*0.58*

TEC2	ACT	BGT	CHP	DPV	GGC	ICG	LCT	MFC	NND	OGC	PFC	SPP	WIND
ACT	*0.01*	-0.03	-0.01	0.00	-0.01	0.02	0.00	0.00	0.00	-0.04	0.04	0.00	-0.04
BGT	-0.03	*9.95*	-0.11	-0.28	-0.75	-0.12	-0.10	0.04	-0.01	0.45	-0.30	-0.09	0.48
CHP	-0.01	-0.11	*0.35*	-0.07	-0.14	-0.04	-0.01	0.09	0.00	-0.04	-0.09	-0.02	0.19
DPV	0.00	-0.28	-0.07	*0.81*	0.19	-0.03	0.01	-0.05	0.00	-0.08	0.01	0.01	-0.94
GGC	-0.01	-0.75	-0.14	0.19	*2.40*	-0.06	0.02	-0.13	0.00	-0.56	-0.05	0.02	-0.89
ICG	0.02	-0.12	-0.04	-0.03	-0.06	*0.33*	0.04	0.00	0.00	-0.14	0.32	0.02	-0.32
LCT	0.00	-0.10	-0.01	0.01	0.02	0.04	*0.16*	-0.01	0.00	0.01	0.05	0.00	-0.10
MFC	0.00	0.04	0.09	-0.05	-0.13	0.00	-0.01	*0.25*	0.00	0.01	0.00	0.00	-0.02
NND	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	*0.00*	0.00	0.00	0.00	-0.03
OGC	-0.04	0.45	-0.04	-0.08	-0.56	-0.14	0.01	0.01	0.00	*3.09*	-0.27	-0.03	0.31
PFC	0.04	-0.30	-0.09	0.01	-0.05	0.32	0.05	0.00	0.00	-0.27	*0.91*	0.03	-0.79
SPP	0.00	-0.09	-0.02	0.01	0.02	0.02	0.00	0.00	0.00	-0.03	0.03	*0.04*	-0.15
WIND	-0.04	0.48	0.19	-0.94	-0.89	-0.32	-0.10	-0.02	-0.03	0.31	-0.79	-0.15	*14.42*

TEC3	**ACT**	**BGT**	**CHP**	**DPV**	**GGC**	**ICG**	**LCT**	**MFC**	**NND**	**OGC**	**PFC**	**SPP**	**WIND**
ACT	*0.00*	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
BGT	0.00	*1.02*	0.00	-0.13	-0.08	0.01	0.00	0.03	0.00	0.02	-0.01	-0.01	0.05
CHP	0.00	0.00	*0.01*	0.00	-0.01	-0.01	0.00	0.00	0.00	0.00	-0.01	0.00	0.00
DPV	0.00	-0.13	0.00	*0.15*	0.03	-0.01	0.00	-0.02	0.00	-0.01	0.00	0.00	-0.10
GGC	-0.01	-0.08	-0.01	0.03	*0.45*	-0.02	0.00	-0.03	0.00	-0.06	-0.03	0.00	-0.06
ICG	0.00	0.01	-0.01	-0.01	-0.02	*0.07*	0.00	0.00	0.00	-0.01	0.06	0.00	-0.01
LCT	0.00	0.00	0.00	0.00	0.00	0.00	*0.00*	0.00	0.00	0.00	0.00	0.00	0.00
MFC	0.00	0.03	0.00	-0.02	-0.03	0.00	0.00	*0.06*	0.00	0.00	-0.01	0.00	0.02
NND	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	*0.00*	0.00	0.00	0.00	0.00
OGC	0.00	0.02	0.00	-0.01	-0.06	-0.01	0.00	0.00	0.00	*0.10*	-0.01	0.00	0.01
PFC	0.01	-0.01	-0.01	0.00	-0.03	0.06	0.00	-0.01	0.00	-0.01	*0.18*	0.00	-0.04
SPP	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	*0.01*	-0.01
WIND	0.00	0.05	0.00	-0.10	-0.06	-0.01	0.00	0.02	0.00	0.01	-0.04	-0.01	*0.80*

TSECUR	**ACT**	**BGT**	**CHP**	**DPV**	**GGC**	**ICG**	**LCT**	**MFC**	**NND**	**OGC**	**PFC**	**SPP**	**WIND**
ACT	*4.16*	5.38	-0.63	0.29	0.38	11.80	0.82	-4.89	0.12	-33.20	18.07	0.69	4.38
BGT	5.38	*412.06*	-29.42	-0.66	-31.27	24.17	2.17	-13.56	0.36	-22.42	44.28	-0.64	17.83
CHP	-0.63	-29.42	*43.81*	-0.42	30.02	-0.34	-0.57	11.51	-0.18	-47.09	-0.21	-4.59	-9.85
DPV	0.29	-0.66	-0.42	*0.94*	-0.57	2.21	0.18	-0.40	0.02	-4.07	3.21	0.55	2.53
GGC	0.38	-31.27	30.02	-0.57	*330.99*	17.51	-1.36	30.36	-0.91	-338.79	14.47	-3.82	7.08
ICG	11.80	24.17	-0.34	2.21	17.51	*82.92*	4.60	-7.71	0.64	-186.62	104.30	4.98	23.35
LCT	0.82	2.17	-0.57	0.18	-1.36	4.60	*0.92*	-0.79	0.06	-11.52	8.29	0.45	1.44
MFC	-4.89	-13.56	11.51	-0.40	30.36	-7.71	-0.79	*54.64*	-0.18	8.11	-12.78	-1.21	-11.64
NND	0.12	0.36	-0.18	0.02	-0.91	0.64	0.06	-0.18	*0.07*	-0.55	1.20	0.02	0.11
OGC	-33.20	-22.42	-47.09	-4.07	-338.79	-186.62	-11.52	8.11	-0.55	*1433.15*	-306.99	-8.15	-69.96
PFC	18.07	44.28	-0.21	3.21	14.47	104.30	8.29	-12.78	1.20	-306.99	*234.10*	7.68	29.51
SPP	0.69	-0.64	-4.59	0.55	-3.82	4.98	0.45	-1.21	0.02	-8.15	7.68	*9.73*	2.34
WIND	4.38	17.83	-9.85	2.53	7.08	23.35	1.44	-11.64	0.11	-69.96	29.51	2.34	*98.10*

II. Integrated R&D Policy Exploration using ISPA

Nikos Kouvaritakis and Vagelis Panos **ICCS-NTUA**

1. Introduction

Central to the SAPIENTIA approach is the elaboration of a small aggregated meta-model named ISPA (Integrating System for Priority Assessment), specifically designed for R&D budgeting policy exploration. In essence, the ISPA model explores the domain of optimal R&D strategies in a context of uncertainty (i.e. incorporating notions of hedging) and in the presence of multiple objectives as is appropriate when considering public sector participation in R&D initiatives. In order to incorporate fully the stochastic characteristics of the problem (enable the analysis of risk averse stances) and at the same time treat the different objectives symmetrically, ISPA is specified as an optimization problem where the probability that an objective exceeds a given threshold is maximised subject to the condition that the probability that the other objectives exceed given thresholds is greater than a certain level. Naturally, the budget allocations must also be kept non-negative.

The key features of ISPA are:

- A single horizon, i.e. the budget allocation is assumed to be decided at some time near the present aiming to obtain some desired effects on a fixed future horizon (an essential feature of this type of exercise where it is clearly understood that allocations in future dates can be postponed and can incorporate knowledge acquired in the meantime).
- In recognition of the essentially speculative character of R&D budgeting ISPA treats the impact of allocation decisions stochastically giving the possibility to make probabilistic statements.
- Statistical dependence of impacts is allowed for, arising from the fact that they are affected (albeit differently) by the same variables that are themselves subject to risk.
- Emphasis has been placed in the quantification of the parameters used for the performance of the definitive policy exploration exercises. These parameters were of two types:
- Reaction functions linking the expected impact of an R&D action on the objectives of the R&D policy as retained.
- Stochastic information (basically variances and co-variances) on these impacts.

Alternative specifications are of course possible as for example setting the goal as the maximisation of the expectation or alternatively the constraints as inequalities on the expectation of the different objectives. Such specifications would result in asymmetric treatment of the objectives rendering the discussion of the presentation of the results somewhat ambiguous. Replacing both the goal and the objective in terms of expectations would effectively destroy the stochastic character of the exercise rendering meaningful risk analysis impossible.

2. The standard ISPA specification

In algebraic terms, the standard ISPA specification has the following structure:

$$\max \Pr\left\{ \sum_j x_j r_{1j}(x_j) > A_1 B \right\}$$

Subject to:

$$\Pr\left\{\sum_j x_j r_{ij}(x_j) > A_i B\right\} \geq p_i$$

$$\sum_j x_j \leq B \qquad x_j \geq 0$$

$$\vec{r}_i \approx \tilde{N}\left(\vec{\rho}_i(\vec{x}), V_i(\vec{x})\right)$$

Where:

- the x(j) are the budget allocations to technology j;
- the r(i,j) are random variables representing the impact on objective i of expenditure on technology j;
- A(i) are the thresholds for each objective and p(i) the probabilities associated to them;
- B is the total R&D budget;
- $\vec{\rho}_i(\vec{x})$ and $V_i(\vec{x})$ are the mean and variance covariance of $\vec{r}_i$ and are functions of $\vec{x}$.

2.1. A more concrete specification of the ISPA meta-model

The new formulation of ISPA considers endogenous p_i and V_i as functions of x:

$$\max_{\mathbf{x}} \frac{\boldsymbol{\rho}_1'(\mathbf{x})\mathbf{x} - A_1 B}{\sqrt{\mathbf{x}'\mathbf{V}_1(\mathbf{x})\mathbf{x}}}$$

, the main objective under consideration

subject to:

$$\boldsymbol{\rho}_i'(\mathbf{x})\mathbf{x} - F^{-1}(p_i)\sqrt{\mathbf{x}'\mathbf{V}_i(\mathbf{x})\mathbf{x}} \geq A_i B$$

, i=2…m the constraints on the other objectives

$$\mathbf{u}'\mathbf{x} \leq B$$

, the budget constraint

$$\mathbf{x} \geq 0$$

, the non-negativity of budget allocation constraint

Where:

- **x** is an n by 1 vector containing the budget allocation for each of the n technological options considered
- $p_i = E(\mathbf{r}_i)$ where the $\mathbf{r}_i$ are n by 1 vectors representing the random impacts of the budget contributions on objective i
- p_i is the probability requirement concerning the ith objective
- u is an n by one unit vector
- A_i represents the threshold associated with the ith objective.
- B is a scalar representing the budget.

3. Integrated Policy Exploration Using ISPA

The reaction functions linking the expected impact of an R&D action on the objectives of the R&D policy along with the stochastic information (variances, co-variances of impacts, joint probability distributions of the productivity of R&D expenditure on individual technologies) as derived from PROMETHEUS in the R&D "shock" exercises (presented in the previous section) have provided the essential numerical input to ISPA, in order to perform the integrated R&D policy assessment. The set of objectives presented in section (…..) has been integrated in the meta-model whereas 39 technological options were considered in the analysis (their classification is provided in Table 3-1)

Table 3-1: Classification of technologies considered in ISPA

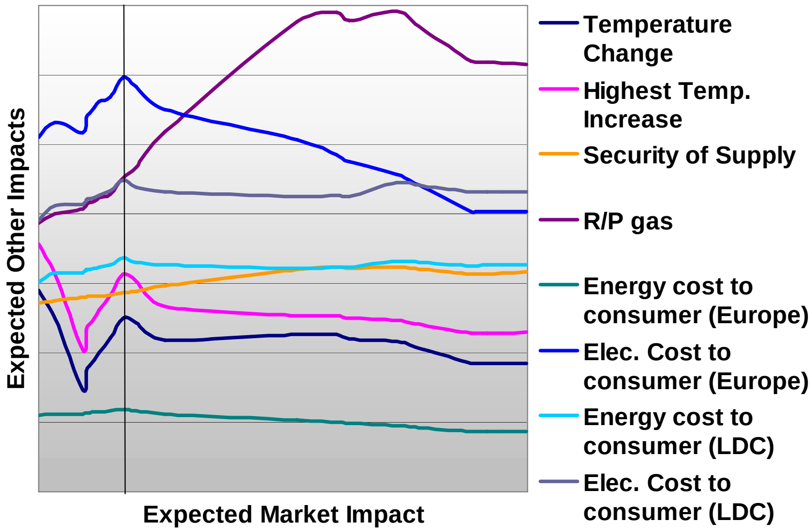
Classification of technologies	# of options
Classical Thermal	4
Clean Coal	2
Gas Turbines	3
Nuclear	3
Biomass	2
Solar	3
Wind	3
CO_2 Capture and Seq.	6
Fuel Cells	2
Hydrogen Production	6
Conventional Vehicles	1
Non Conventional Vehicles	2
Other	2
TOTAL	**39**
of which D&D	*5*

The policy integration tool offers a large number of possibilities for policy exploration. To begin with, a feasible set is defined representing for each objective thresholds for the impact of R&D and minimum probabilities that they will be exceeded. The exploration proceeds by placing each sustainable development objective in the principal objective position, allowing the minimum threshold regarding it to be increased and maximising the probability of achieving it. This implies that the expectation regarding this objective is raised under conditions of hedging while satisfying minimum requirements on other objectives. This process is repeated placing other indicators on the principal objective position. Successive solutions lead to the construction of a series of pay-off curves. Of particular interest on these pay-off curves are turning points. Such turning points indicate solutions where a gain in one objective can only be achieved at the cost of deterioration on another (i.e. they mark the end of synergy on the two objectives). Sets of such solutions are collected and examined for common traits indicating robust results as well as divergences. In the presence of divergent policy mixes, "compromise" solutions could be obtained by using rules and methods developed for multiple criteria optimisation.

The exploration procedure adopted starts from the existing public R&D budget to construct the feasible set by exploiting synergies among the objectives. The solution obtained is then improved by consolidating synergies and relaxing bounds and, finally by sacrificing the probability (or the threshold) requirements for some objectives. Guidance in the relaxation and the sacrificing has been provided by the shadow costs.

For the initial exercise market impact was used as the main objective while the sustainable development objectives operating via the constraints. The market impact threshold was raised in small steps while satisfying minimum requirements on other objectives. This process led to the construction of the pay-off curves presented in the figure below. An interesting finding within this excercise has been the identification of broad synergies between expectations on the sustainable development targets on the one hand and on market impact on the other.

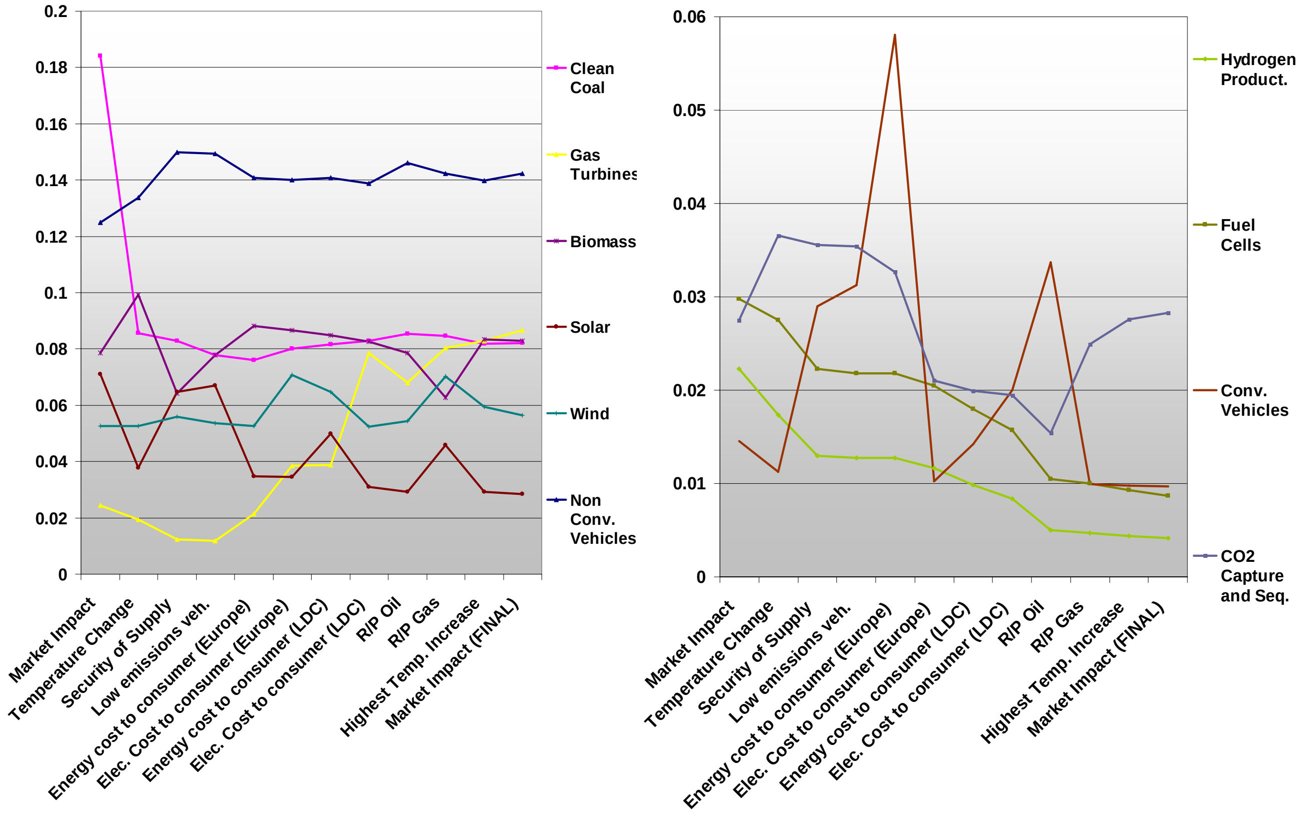
Figure 3-1: Example of pay-off and compromise chosen



An inspection of the pay-off curves indicates that there is a clear peak in the pay-off curves of nearly all secondary objectives, at the points where the curves are intersected by the vertical line. Beyond this point, improvements in the expected market impact are only obtained at the expense of inferior performance in terms of almost all the other objectives. For example beyond this point, the expected market impact can be improved only at the expense of energy and electricity cost reductions to the consumers in Europe and the developing world. Likewise, the expected impact on temperature change and on highest temperature increase does not grow beyond the point where their pay-off curves are intersected by the vertical line. Exception to this is the broad synergy between expectations on market impact on the one hand and security of supply on the other (notably gas security of supply) even at high levels of market impact ambition. However, this broad synergy appears to occur only at the expense of the expectations on almost all secondary objectives. In view of the above, the compromise (low regret) solution chosen is marked by the vertical line which passes through the turning points of most pay-off curves. Having found this ‘satisfactory’ (compromise) for the market impact objective solution, this solution was ‘frozen’ as a constraint and then another objective was placed in the main position, increasing gradually its expectation.

The budget allocations derived during this exploration process are presented in figure 11 below. The budget allocation on the compromise point of the previous graph is the starting point. As the exploration proceeded by placing each other objective in the main objective position, the corresponding budget shares are presented; the market impact objective is eventually re-placed at the main objective position and the final budget shares, as shown by the final points in the graphs are derived.

Figure 3-2: Budget shares during the exploration process



A summary view of the budget results arising from the whole range of exercises follows. Non conventional vehicles receive the highest shares (approximately 12.5 to 15 percent) irrespective of the target that was placed as the main objective. Clean coal technologies feature strongly in almost all the cases examined (budget shares of around 8 percent), inlcuding those that gave priority to temperature change. Among renewables, biomass attracts the higher funding in all the exercises carried out (6 to 10 percent of the budget), with the exception of the case where priority is given to the gas resources to production ratio when it was overtaken by wind, (but still maintained over 6 percent of the budget). Wind gets around 5 percent of the budget in all exercises performed with the exception of the cases where the gas r/p ratio and the electricity cost to the consumer in Europe is prioritised; in these two cases wind's share rises to around 7 percent. Solar thermal in turn tends to get higher funding when security of supply, introduction of low emission vehicles and also consumer cost reductions in developing countries are set as the main targets.

Gas turbines, characterised by relatively low emissions, large and reasonably secure market penetration prospects feature strongly in the exercises when market impact, highest temperature increase, gas security of supply and electricity costs to consumers especially in less developed regions were given priority, attracting shares between 7 and over 8 percent of the budget. Their share is halved when electricity cost to the european consumer and energy cost to the developing world consumers were given priority. In the remaining cases gas turbines are directed less than two percent of the budget.

Conventional vehicles are restricted to low shares of the budget, displaying shares below 3.5 percent of the budget in most cases with the exception of the case where priority was given to energy cost reductions to european consumers, where they get a share close to 6 percent.

CO_2 capture and sequestration technologies register shares between 1.5 and 3.5 percent in the exploration exercise. They are particularly favoured when temperature change, security of supply and low emission vehicles are the dominant concern.

Fuel Cells and Hydrogen production technologies are restricted to low shares (less than 3%) irrespective of the target that was placed as the main objective. They tend to attract more funding when temperature change and security of supply were given emphasis and the least when market impact is given priority.

4. The MIP specification of ISPA

Using the PROMETHEUS stochastic model, a comparison of the impacts on SD objectives obtained by the baseline projected GERD allocation with the impacts obtained by using the ISPA allocation was delivered. The results showed that the ISPA allocation improves relatively slightly the mean values but has much greater effect on the probabilities of obtaining impacts. The solutions obtained using ISPA turn out to be highly conservative sacrificing unduly expected impact in an effort to secure minimum requirements. Part but not all of the reason why this is so, lies in the assumption of normality of the impacts distribution (which is not the case according to PROMETHEUS results). Therefore, a Mixed Integer Programming (MIP) specification has been tested. In algebraic terms the Mixed-Integer Programming specification of ISPA becomes:

$$\max_{\mathbf{x},\mathbf{W}} \quad \mathbf{u}'\mathbf{w}_0$$

Subject to:

$$\begin{gathered}
(\mathrm{A}_i + s)\mathbf{w}_i - \mathbf{R}_i\mathbf{x} \le s\,\mathbf{u} \qquad i = 0,\dots,m \\
\mathbf{W}'\mathbf{u} \ge s\,\mathbf{p} \\
\mathbf{u}'\mathbf{x} \le 1 \\
\mathbf{W} \in \{0,1\}^{s(m+1)} \ \mathbf{x} \in \mathrm{B} \subset \Re^{+n}
\end{gathered}$$

Where:

- m, is the number of probability constraints.
- n, is the number of R&D options.
- s, is the number of experiments in the Monte Carlo sample.
- The subscript 0 is reserved for the main objective.
- A_i, are the thresholds required to be exceeded at given probabilities contained in the vector **p**.
- **x** are the R&D budget shares.
- **W** is a matrix of 0-1 variables signifying which experiment is taken into consideration in each constraint
- $\mathbf{R}_i$ are matrices containing normalised impacts as calculated using PROMETHEUS
- B is an optional set of linear restrictions on the R&D allocations

This specification provides complete flexibility on the joint distributions of the impacts as it can handle non-symmetric and non-unimodal distributions and take automatically into account complex co-variance patterns. In addition, no illegal values (according to PROMETHEUS or common logic) are considered. It also respects PROMETHEUS results rendering analytical walk-back feasible. This approach expands the possibilities for adopting different risk-averse stances as it has no restriction to probabilities greater than 50% and it can handle non-convexity.

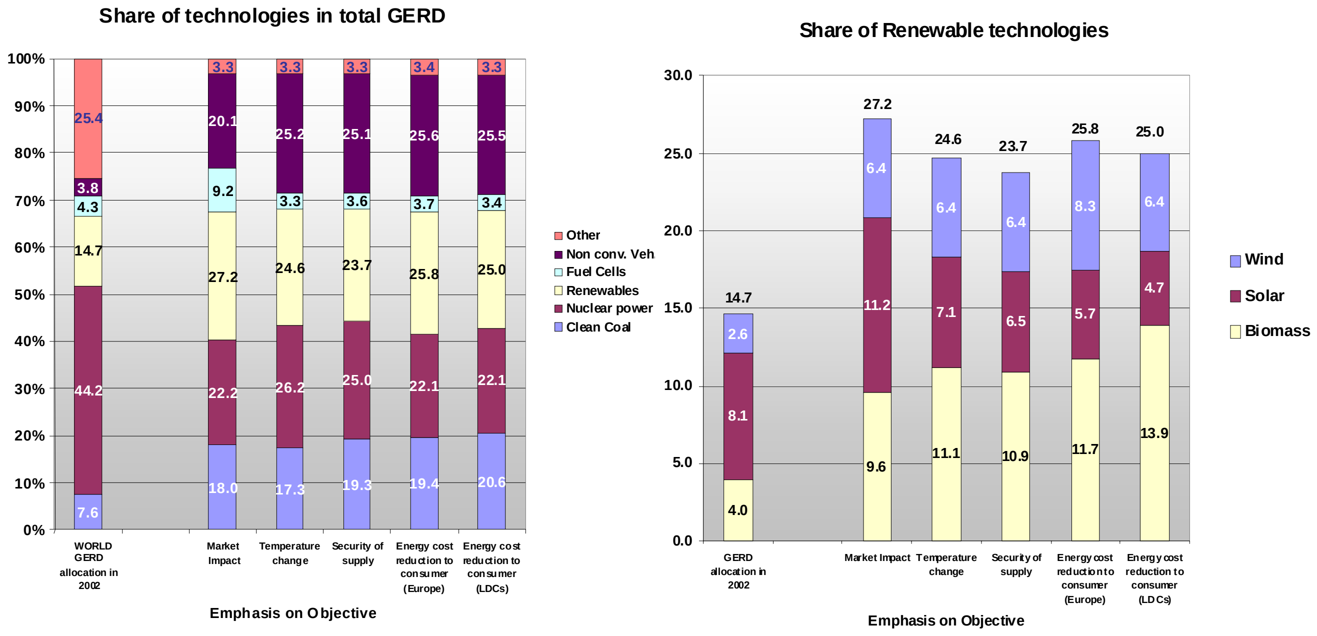
However, the MIP version of ISPA has some disadvantages. Computational difficulties imply long and sometimes erratic solution times, restricting the number of possibilities that can be explored. The introduction of non-linearities of expected impacts has also posed difficulties. Finally, the possibilities for using shadow costs (dual values) to guide the exploration were limited. With familiarity with the problem useful shortcuts were found that reduced the computational time required. However, the difficulties in introducing non-linearities of expected impacts limit the MIP specification to the exploration of relatively low budgets.

4.1. Using the MIP Version of ISPA for budget exploration

The first task in the utilization of the MIP version of ISPA for budget exploration consists in specifying fairly ambitious expectations targets for all objectives. The exploration proceeds by giving emphasis on one objective at a time, seeking higher expectations and lower risks. Exploiting synergies allows to consolidate gains both in terms of expectations and risks. By setting ambitious targets on all objectives simultaneously the budgets obtained are both diversified in terms of technologies included and fairly stable, despite shifts in emphasis.

The figures below summarise the optimal budgets obtained in these sets of exercises. The share of renewables is further disaggregated on the right.

Figure 4-1 Exploration procedure summary results



The budget exploration exercises have been performed assuming increases to the projected public R&D allocations of a relatively modest size compared to the baseline. In this sense, they are marginal in nature and depend on the allocations assumed in the baseline. Non conventional vehicles (mostly electric and hybrid) represent five to seven times larger shares in the exploration exercise relative to their recent funding. They attract shares from 20 to 26 percent of the budget in all cases examined and appear to benefit from relative independence from impacts of allocations on other technologies. Electric and Hybrid vehicles are particularly favoured when emphasis is placed on urban transport and costs to consumers (but also security of supply and climate change) but tend to display the lowest shares when emphasis is placed on market impact (giving way mostly to fuel cells).

Nuclear power options get appreciably lower shares than recent public R&D allocations (of around 44%). They are allocated 22 to 26 percent of the R&D budget in all exercises, of which approximately 14 percent corresponds to 2nd and 3rd generation nuclear. Their prospects are more attractive when priority is given to climate change, security of supply and gas resource depletion.

Clean coal technologies feature strongly in all the cases examined, displaying double to triple shares relative to the 2002 world public R&D allocation. This group of technologies attracts 17 to 20 percent of the budget allocation in all exercises examined. Due to negatively correlated prospects with most of the other options, their support constitutes a major hedging instrument especially with regard to meeting binding probability constraints on secondary objectives.

Integrated coal gasification features strongly in the solutions, displaying more attractive prospects when emphasis is placed on consumer costs in less developed countries. This technology also plays an instrumental role for meeting security of supply and gas resource depletion probability constraints (in cases of failure of 4th generation nuclear).

Renewable technologies are allocated substantially higher R&D effort in all exercises performed. Solar technologies are more effective in terms of market impact, but in all other cases their shares are markedly lower. They tend to get lower funding when energy costs to consumer are set as the main objective. On the other hand, biomass attracts low funding when market impact is given priority but is particularly favoured when energy cost reductions to consumers in the less developed countries are the dominant concern.

Fuel Cells are particularly favoured when market impact is given priority (attracting close to 10% of the budget allocation) due mainly to relatively high (albeit more uncertain) prospects to 2050. However, when emphasis is placed on other targets, their rather ambiguous and volatile impacts mean that their share falls to only 3.5% of the allocation. Carbon capture and sequestration technologies, which are characterised by relatively poor improvement prospects but are favoured already in the baseline R&D projection, attract only 0.5 to 0.55 percent of the budget, mostly playing the role of hedging against high energy costs due to possible very high carbon values.

4.2. Summary Conclusions

The overall analysis within SAPIENTIA indicates that R&D is broadly a cost effective way of addressing a large number of SD objectives. Some SD concerns however necessitate large scale changes and R&D alone cannot make a major impact. A certain amount of re-direction of GERD could prove effective in pursuit of sustainability on many fronts. It could also prove a fine balancing act because of important secondary effects.

Modelling energy technology dynamics has rendered quantitative integrated R&D policy exploration possible. Diversified and robust solutions emerge, taking into consideration multiple objectives, synergies of R&D actions and the structure of uncertainties. Still, a lot remains to be done in terms of dissemination of the methodology developed before it can be applied directly on R&D policy formulation.

List of Figures

List of Tables