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WP3: Electricity generation technologies and system integration.

Environmental aspects of integration of decentralized generation into the overall electricity generation system

TASK REPORT

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1. Objectives

The objective of this task is to analyse, from an environmental point of view, the electricity generation technologies with an horizon of 2030-2050.

The technologies under scope are:
- Coal fired technologies
- Oil & gas fired technologies (CCGT)
- Combined heat and power
- CO_2 capture and storage (CCS), and
- Biomass gasification

2. Methodology

The methodology used to perform this task is largely based in the Life Cycle Analysis methodology. Available published information on impact categories, methods and indicators -CML guidelines (Guinée *et al*, 2001), the Ecoindicator methodology (Goedkoop and Spriendsma, 2000) among others- has been reviewed, and among them the CML impact assessment method has been chosen. CML is a method developed in the Centre of Environment Science of the Leiden University in The Netherland.

Following the ISO 14042 requirements, first a list of impact categories has to be defined, and characterisation factors for relating the environmental loads to suitable category indicators for these impacts have to be selected. Then, the results of applying those factors are calculated and, afterwards, normalised to indicate the share of each of them in a regional total. Finally, the normalisation results are grouped and weighted to include societal preferences of the various impact categories.
The result of applying this methodology is a final score for each technology which allows to make a well-balance comparison between them and also along between the different time periods.

2.1. Impact categories

In the impact assessment phases, the results of the inventory analysis are translated into contributions to relevant impact categories which have to be previously identified. The inventory analysis has consisted of defining all the inputs from the environment (raw material, fuels) and outputs to the environment (energy, emissions), which enter and go out of the power generation facility.
For each technology, technical, economic and environmental data has been collected by other task participants. The results of the inventory have been some tables, in the format of table 5 in Appendix A, from which ecology and resource use data have been extracted and used in this work.

The CML impact assessment method considers the following categories of impacts:

IMPACT CATEGORIES
Abiotic Depletion

Global Warming
Human Toxicity
Fresh Water Aquatic Ecotoxicity
Marine Aquatic Ecotoxicity
Terrestrial Ecotoxicity
Photochemical Oxidation
Acidification
Eutrophication

Table 1. Impact categories

- Abiotic depletion refers to the exhaustion of natural resources such as iron ore or copper, which are regarded as non-living. Impacts considered are those derived from the extraction of minerals and fossil fuels.
- Global warming is the impact of greenhouse gases emissions on the radiative forcing of the atmosphere. These emissions have negative impacts on human and ecosystem health, and material welfare.
- Human toxicity includes the impacts on human health of toxic substances emitted to the environment.
- Fresh water aquatic ecotoxicity refers to the impact of toxic substances emitted to freshwater aquatic ecosystems.
- Marine aquatic ecotoxicology refers to the impact of toxic substances emitted to marine aquatic ecosystems.
- Terrestrial ecotoxicity refers to the impact of toxic substances emitted to terrestrial ecosystems.
- Photochemical oxidation is the formation of reactive chemical compounds, such as ozone, by the action of sunlight on certain primary air pollutants. These compounds may be injurious to human health, ecosystems, materials and crops.
- Acidification is the result of acidifying pollutants emissions, such as SO_2 or NOx, to the air. These emissions have negative impacts on soil, groundwater, surface waters, biological organisms, ecosystems and materials.
- Eutrophication is the consequence of high levels of macronutrients, such as nitrogen and phosphorus, in the environment.

2.2. Classification and characterization of the environmental loads

In the classification phase, the qualified and quantified environmental loads are assigned, on a qualitative basis, to the impact categories. For instance, CO_2 emissions in $kgCO_2/kWh$ are assigned to the global warming impact category. NOx emissions in kgNOx/kWh are assigned to the human toxicity, photochemical oxidation, acidification, and eutrophication impact categories.

In the characterisation step, the environmental loads previously assigned qualitatively to one or more impact categories in the classification phase, are quantify in terms of a common unit for that category by using characterization factors. Then, each impact category has a category indicator result. For instance and following with the previous examples, all the emissions related to the global warming category impact are multiplied by a characterisation factor, different for each pollutant, being the result the relative contribution of the substance to this impact category. All the results are now in the same units, in this case $kgCO_2$ eq/kWh, and can be added to obtain a single score for this impact category. The set of all the category indicators results is called the environmental profile.

The characterisation factors and units used in CML are defined as follows:

- Abiotic depletion: the characterisation factor is the potential of abiotic depletion of the extraction of those minerals and fossil fuels. The unit of the characterisation factor is kg of antimony (Sb) equivalents per kg of extracted mineral.
- Global warming: the characterisation factor is the potential of global warming of each greenhouse gas emission to the air. The unit of the characterisation factor is kg of carbon dioxide (CO_2) equivalents per kg of emission.
- Human toxicity: the characterisation factor is the potential of human toxicity of toxic substances emitted to the air, water or/and soil. The unit of the characterisation factor is kg of 1,4-dichlorobenzene (1,4-DB) equivalents per kg of emission.
- Fresh water aquatic ecotoxicity: the characterisation factor is the potential of fresh water aquatic toxicity of each substance emitted to the air, water or/and soil. The unit of this factor is kg of 1,4-DB equivalents per kg of emission.
- Marine aquatic ecotoxicology: the characterisation factor is the potential of marine aquatic toxicity of each substance emitted to the air, water or/and soil. The unit of this factor is kg of 1,4- DB equivalents per kg of emission.
- Terrestrial ecotoxicity: the characterisation factor is the potential of terrestrial toxicity of each substance emitted to the air, water or/and soil. The unit of this factor is kg of 1,4- DB equivalents per kg of emission.
- Photochemical oxidation: the characterisation factor is the potential of photochemical ozone formation of each substance emitted to the air. The unit of this factor is kg of ethylene (C_2H_4) equivalents per kg of emission.
- Acidification: the characterisation factor is the acidification potential for each acidifying emission to the air. The unit of this factor is kg of sulfur dioxide (SO_2) equivalents per kg of emission.
- Eutrophication: the characterisation factor is the potential of eutrophication of each eutrophying emission to the air, water and soil. The unit of this factor is kg of phosphate ion (PO_4^{--}) equivalents per kg of emission.

2.3. Normalization of the calculated results for each impact category.

Normalization serves to indicate the share of the results in a worldwide or regional total. Although it is not an essential step in life cycle analysis methodologies, it is strongly recommended to undertake normalisation to understand the relative importance and magnitude of the results for process or product. Moreover, in our study it is indispensable to reach a single score for each technology in order to compare the environmental benefits/damages of them.

In the normalization phase, the results of the characterization step for the alternative technologies are related to a reference situation. In other words, the magnitude of the indicator results has to be calculated against reference data from the same reference area. This reference information may be related to a given community, country or region over a period of time. In our case we have chosen a normalisation method applicable to the European region. Among the ones included in CML, the

West-Europe factors for normalisation have been chosen as they are the ones that better fit in our study. Those factors are as follows:

IMPACT CATEGORY	NORMALIZATION FACTOR
Abiotic depletion	1.06E+10
Global warming	4.73E+12
Human toxicity	7.57E+12
Fresh water aquatic ecotoxicity	5.05E+11
Marine aquatic ecotoxicity	1.14E+14
Terrestrial ecotoxicity	4.73E+10
Photochemical oxidation	8.24E+09
Acidification	2.74E+10
Eutrophication	1.25E+10

Table 2. Normalization factors

After normalisation, results are given in the same unit and all the normalised indicator results corresponding to each impact category can be added. A single score for each technology is then obtained.

2.4. Valuation step.

The last phase in the impact assessment is the weighting. In this phase the normalized indicator results for each impact category are assigned numerical factors according to their relative importance, multiplied by these factors and aggregated into a **single score** that represents the environmental performance of each technology.

Weighting factors may be chosen by expert panels. As there is not a recommended set of weighting factors, we have used the ones resulting from a social panel approach (Guinée *et al*, 2001):

IMPACT CATEGORY	WEIGHTING FACTOR
Abiotic depletion	0.01
Global warming	2.4
Human toxicity	1.1
Fresh water aquatic ecotoxicity	0.2
Marine aquatic ecotoxicity	0.2
Terrestrial ecotoxicity	0.4
Photochemical oxidation	0.8
Acidification	1.3
Eutrophication	1.0

Table 3. Weighting factors

3. Results

Final results of the impact assessment of the power generation phase for each technology are shown in table 4, and represented in figure 1. A ratio between the lowest score of the present technologies and the others has also been calculated.

TECHNOLOGY	SCORE	RATIO
BIOMASS GASIFICATION	6.90E-14	1.00
NATURAL GAS CC CCS 2010	6.64E-14	0.96
NATURAL GAS CC CCS 2020	6.48E-14	0.94
NATURAL GAS CC CCS 2030	6.40E-14	0.93
LIGNITE IGCC CCS 2010	1.46E-13	2.12
LIGNITE IGCC CCS 2020	1.37E-13	1.98
LIGNITE IGCC CCS 2030	1.33E-13	1.93
CCGT	1.97E-13	2.86
LIGNITE IGCC	5.21E-13	7.56
LIGNITE IGCC 2010	4.95E-13	7.18
LIGNITE IGCC 2020	4.67E-13	6.77
LIGNITE IGCC 2030	4.63E-13	6.71
LIGNITE ST	5.27E-13	7.64
LIGNITE ST 2010	5.17E-13	7.49
LIGNITE ST 2020	4.69E-13	6.80
LIGNITE ST 2030	4.69E-13	6.80

Table 4. Impact assessment results

CC: Combined Cycle

CCS: CO_2 Capture & Sequestration

IGCC: Integrated Gasification Combined Cycle

CCGT: Combined Cycle Gas Turbine

ST: Steam Turbine

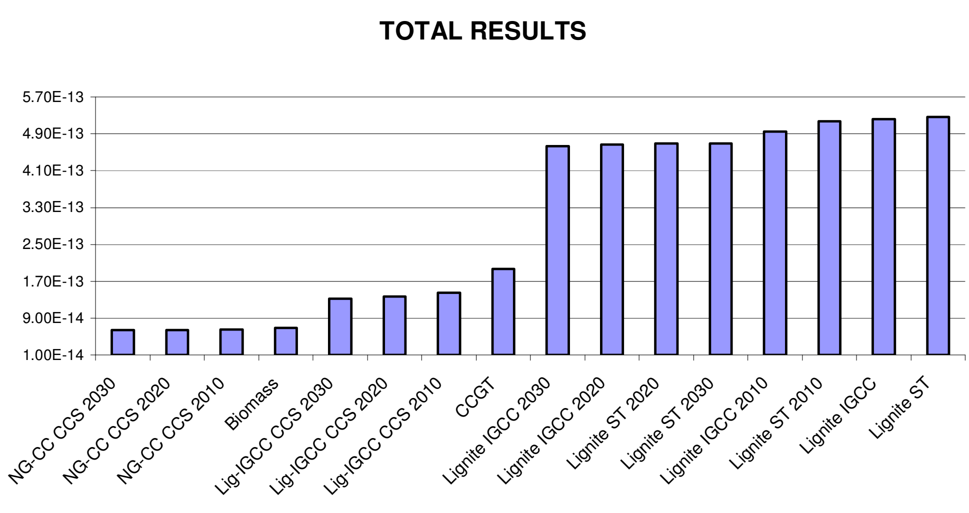

Figure 1. Total impact assessment results

For the present technologies, the lower impacts correspond to the biomass gasification technology followed by the CCGT one, while the highest are those from the lignite technologies. For the future technologies, those with CO_2 capture and sequestration show the best results, in fact the results are the lowest of all the technologies analysed.
Analysing the different impact categories, the more relevant are: global warming, acidification, photochemical oxidation, and eutrophication. Global warming is the main impact in the fossil fuel technologies without CCS. When CCS is available as well as in the biomass gasification technology, acidification is the category with the highest scores. Between results for eutrophication and photochemical oxidation, differences are slight for the fossil fuel technologies. However, in biomass gasification, eutrophication is much relevant that photochemical oxidation.

In addiction, technologies have been compared for each of the impact categories with the higher scores: global warming, acidification, photochemical oxidation and eutrophication.

3.1. Global warming

The technology which contribute to a greater extent to the global warming impact is the lignite steam turbine follow by the lignite IGCC. On the other hand, natural gas combined cycle with CO_2 capture and sequestration and biomass gasification technologies give the lower impact assessment results. Figure 2 shows global warming impact values for all the technologies during the electricity generation phase.

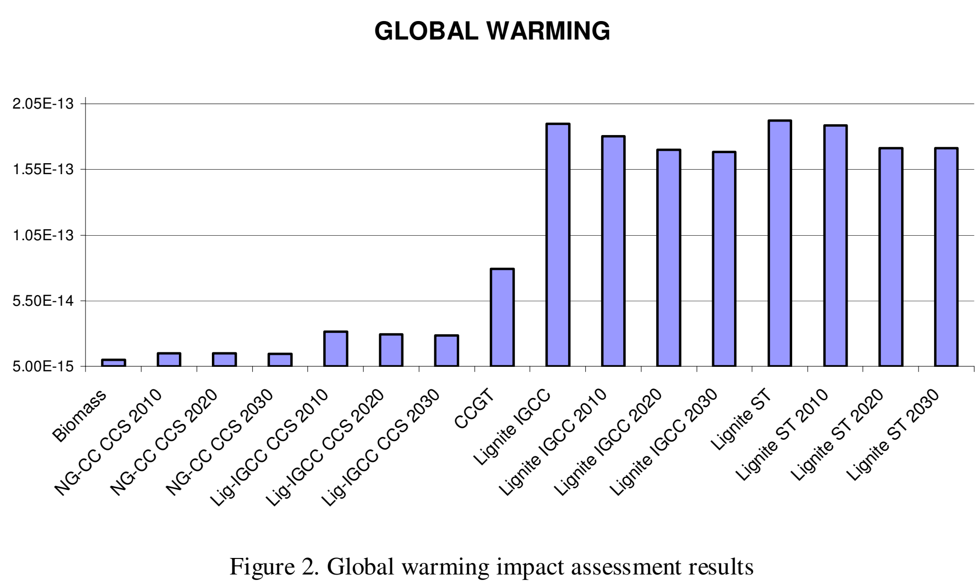

Figure 2. Global warming impact assessment results

Differences in the Lignite IGCC technologies results when introducing CO_2 capture and sequestration can be seen in figure 3.

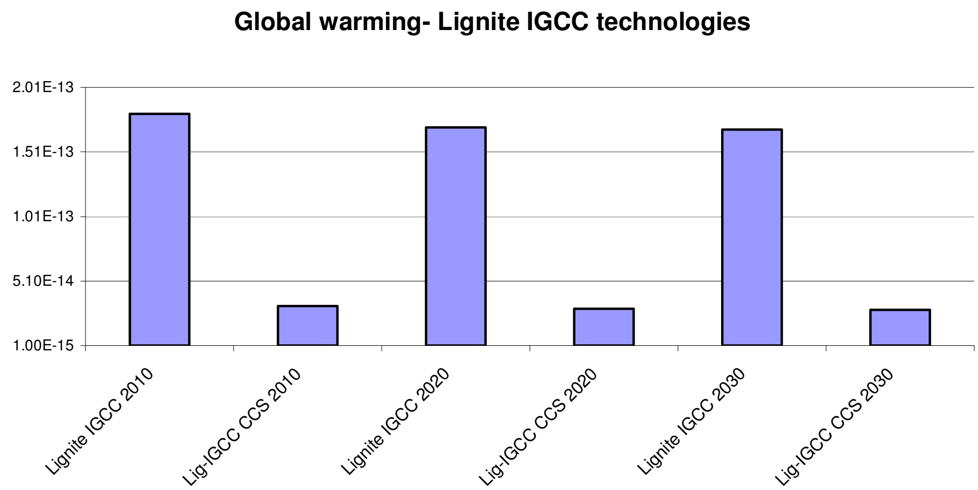

Figure 3. Global warming impact assessment results for Lignite IGCC technologies

3.2. Acidification

Acidification impacts are bigger for the lignite technologies, present and future. For the technologies with CCS, acidification is the main impact. Figure 4 shows acidification impact values for all the technologies during the electricity generation phase.

For the present lignite technologies, acidification values are four times smaller than global warming ones. However, for the future technologies with CCS, both, acidification and global warming impacts are very similar. For CCGT, global warming is much higher than acidification. In fact, for CCGT, acidification represents the lowest result.

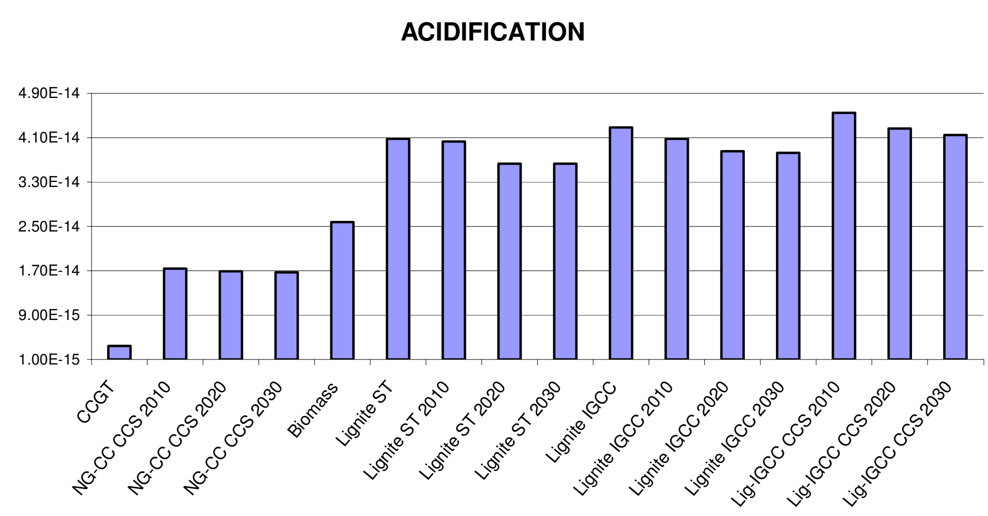

Figure 4. Acidification impact assessment results

3.3. Photochemical oxidation

As for acidification, photochemical oxidation impacts are bigger for the lignite technologies, present and future. Figure 5 shows photochemical oxidation impact values for all the technologies during the electricity generation phase.

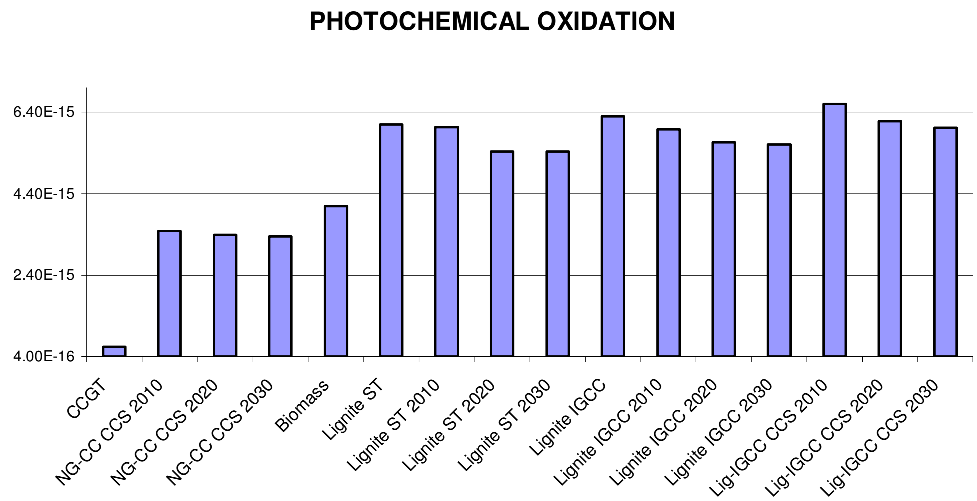

Figure 5. Photochemical oxidation impact assessment results

3.4. Eutrophication

Eutrophication impact results are approximately in the same range than the photochemical oxidation ones. The highest data corresponds to biomass gasification technology due to the N compound emissions: NOx into the atmosphere, and N and NH_4 into water. The lowest corresponds to CCGT, which N compounds emission into water are negligible. Figure 6 shows eutrophication impact values for all the technologies during the electricity generation phase.

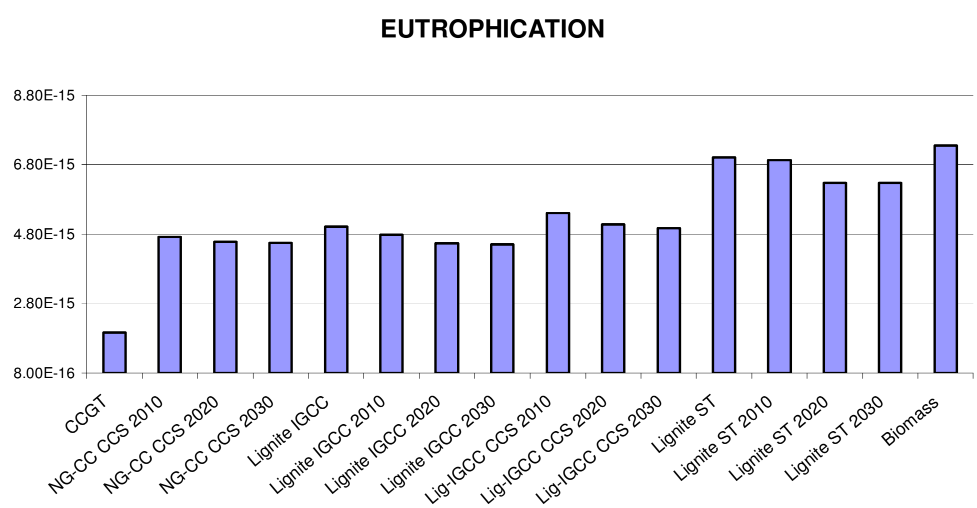

Figure 6. Eutrophication impact assessment results

4. Conclusions

For current technologies, biomass gasification and CCGT have turned out to have the lowest impacts while lignite ones have had the highest results.
For future technologies, those with CO_2 capture and sequestration showed the best results.
Regarding the different impact categories, the more relevant, from highest to lowest, have been global warming, acidification, eutrophication, and photochemical oxidation.

Figure 7 shows all the technologies and the results of the assessment of the four more relevant impact categories.

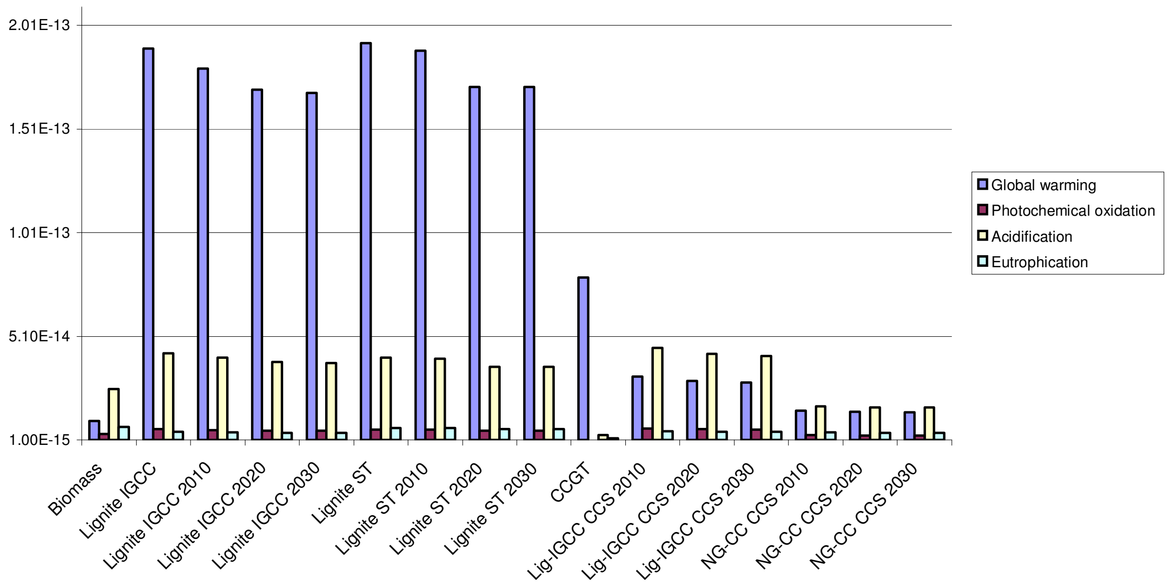

Figure 7. Impact assessment results

In this figure the contribution of each impact category to the total can be seen for each technology.
Global warming is the main impact in the fossil fuel technologies without CCS, but when CCS is available acidification is the category with the highest scores. Eutrophication and photochemical oxidation results hardly showed differences, except for biomass gasification for which eutrophication is much relevant.
Finally, as it was expected, future fossil fuelled technologies gave lower impact results than current ones.

5. Bibliography

§ The Eco-indicator 99. A damage oriented method for Life Cycle Impact Assessment. Methodology report. Goedkoop and Spriendsma, 2000.
§ Life Cycle assessment. An operational guide to the ISO standards. Final report. Guinée *et al*, 2001.

6. Appendix A

Appendix A

Table 5.

Energy:

	Technology
1) Range of unit size and project size [MW] 2) Nominal efficiency *i) For electricity generation only [%]* *ii) For combined heat and power [%]* 3) Efficiency at partial load 4) Flexibility towards fuel, fuel resource availability, plant siting and infrastructures (e.g. cooling water needs, high voltage, grid gas pipes, etc.) 5) Flexibility towards exploitation: *i) Cold start [minutes from 0% to 90% of nominal power]* *ii) Warm/lukewarm start [minutes from 0% to 90% of nominal power]* *iii) Uncontrollable variation in load [% from nominal power]* **Total energetic score**	

Ecology and resource use:

1) Exhaust: *i) CO_2 [kg/kWh$_{electricity}$]* *ii) SO_2 [kg/kWh$_{electricity}$]* *iii) NO_x [kg/kWh$_{electricity}$]* *iv) PM_{10} [kg/kWh$_{electricity}$]* *v) NMVOC [kg/kWh$_{electricity}$]* *vi) Methane [kg/kWh$_{electricity}$]* *vii) N_2O [kg/kWh$_{electricity}$]* *viii) C_{14} [kg/kWh$_{electricity}$]* *ix) Heavy metals [most important ones, g/kWh$_{electricity}$]* 2) Thermal exhaust [TJ/GWh$_{electricity}$] *i) Into air* *ii) Into water source* 3) Liquid waste *i) Total liquid waste [kg/kWh$_{electricity}$]* *ii) Total nitrogen into water source [kg/kWh$_{electricity}$]*	

iii) *Total phosphor into water source [kg/kWh$_{electricity}$]* iv) *Total chlorides into water source [kg/kWh$_{electricity}$]* v) *Total sulfates into water source [kg/kWh$_{electricity}$]* vi) *Others ($KMnO_4$, iron, organic materials, solid materials)* 4) Solid waste [tons/MWh$_{electricity}$] i) *Flue dust* ii) *Slurry* iii) *Hazardous waste* iv) *Radioactive waste* v) *Other solid waste*	 Total:
5) Safety and health impacts i) *Population affected by worst perceived accident during operation [nr of persons]* ii) *Number of deaths over the fuel cycle [persons/MWh$_{electricity}$]* iii) *Other effects* 6) Visual impact and noise 7) Footprint and use of resources i) *Primary material moved for construction [kg/kW$_p$ of nominal power* ii) *Secondary material moved for construction [kg/kW$_p$ of nominal power* iii) *Main materials uses for construction (five) [kg/kW$_p$ of nominal power]*	 1 2. 3. 4. 5.
iv) *Primarily material moved for usage e.g. fuel [tons/ MWh$_{electricity}$]* v) *Secondary material moved for usage e.g. fuel [tons/ MWh$_{electricity}$]* vi) *Critical materials in construction and usage (materials that may become a limiting factor for the technology) [kg/kW$_p$ of nominal power]*	
Total ecological score	

Economy (without subsidies, price level for 2003):

1) Investment cost [euro/MW] 2) Availability [hours per year] 3) Operational time [hours of nominal power/year] 4) Reliability [%] 5) Technical life span [years] 6) Construction time [years]	

7) Fuel cost [euro/MJ] 8) Operation and Maintenance (O&M) cost [euro/$MWh_{electricity}$] 9) Waste handling and dismantling [euro/ $MWh_{electricity}$] **Total economic score**	