

EUSUSTEL WP3 Report on Nuclear Fission  
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# 1. Introduction

There seems to be a worldwide comeback of nuclear power because of two reasons. Firstly because nuclear energy is economically competitive, secondly because of global warming since nuclear energy does not emit greenhouse gases while it produces electricity. The noticeable increase of the price of oil, coal and gas is at the origin of this situation. While gas was an interesting alternative to nuclear power several years ago, the price increase makes it less interesting nowadays.

Renewable energies have been used since Man has discovered fire (about 500,000 years from now), fossils fuels have been used for nearly two centuries and nuclear energy for about half a century only. Therefore it is a rather young energy and, although the basic approach has not changed, significant improvements have been and continue to be done.

## *1.1 The European Union produces one third of its electricity with nuclear power*

Since the oil crisis, in the seventies, several European countries have chosen nuclear power to produce electricity. It turns out to be a reliable source which has the advantage of producing a kWh at a competitive price which remains stable over several decades. In the total cost of the electricity, natural uranium represents only 5%. However, several operations (conversion, enrichment, reprocessing, ...) increase the cost of the fuel which, in the end, represents about 20% of the final price (OCDE 2002). Nevertheless, most of these transformations are done in Europe. It is in this respect interesting compared to fossil fuels. If the price of natural uranium is for example multiplied by a factor 10, the price of the kWh increases by less than 40%. For natural gas, an increase by a factor of 10 of the price of the gas leads to a kWh which is about 7 times more expensive.

There are several possibilities to exploit nuclear energy because fission can be induced either by slow or fast neutrons. Around the world, nuclear electricity is presently entirely produced by slow energy neutron reactors (called also thermal reactors). Among them, water reactors are the dominating technology. In Europe, most of the nuclear plants use light water although a few water-graphite reactors or gas-graphite reactors still exist.

## *1.2 Advantages and disadvantages of nuclear energy*

Apart from economical considerations, an advantage of nuclear energy is that it does not emit carbon dioxide while producing electricity. A very small amount is nevertheless produced by side operations like transportation or when building the plant (because, for example, manufacturing concrete requires energy). A global

evaluation leads to CO<sub>2</sub> emission of about 4-6g per kWh. This figure depends of course very much on way the enrichment process is done, in particular upon the nature of the electricity used for it. At any rate this is much smaller than typical coal plants, for example, which emit of the order of 1000g of CO<sub>2</sub>/kWh, about 2 times more than a gas plant. Nuclear power plants have also a rather good availability rate (up to 80%) which could be improved.

A nuclear plant acts somehow like an energy stock. When it is refueled, it can produce electricity for quite a while. This latter can be optimized to satisfy the electricity demand which may depend upon seasons, short-term uncertainties, etc.

However, as many other energy sources, nuclear energy produce waste and those are of particular nature because a small part of them has a long life time while other are highly radioactive although they do not live long. The basic question is how to manage nuclear waste in a safe and sustainable way. There are already scientific and technological solutions which are continuously improved but no definite political choice has been made at the moment. Research has also allowed reducing drastically the quantity of waste and some of them could possibly be transmuted in the future, reducing still the final waste. However, there will always remain some amount of waste which should be taken care of.

Another point about nuclear energy is the risk of proliferation to military ends. This is a very sensitive topic which requires deep attention at the international level. Finally, electricity production, using nuclear energy is not as flexible as gas turbines. The reason is that it is not easy to quickly modulate power over a large scale. This restricts somehow nuclear electricity generation to the base-load or semi-base load, even if some tricks can be used to modulate the electricity supply.

### *1.3 Safety and waste*

Safety is a basic issue. In Europe, this point has received much attention and safety of nuclear plants is well mastered. No serious accident has ever happened since the mid-fifties, and strict protocols and safety rules are applied to all plants. Severe inspections control that the work is done properly.

As far as waste are concerned, many of the European countries using nuclear energy reprocess the used fuel to decrease the amount of final waste. Important R&D programs are devoted to this subject as well as for waste management. There are long political and public discussions, and debates, which slow down possible choices. Nevertheless, there are still some people against the use of nuclear energy. The fact that there are opponents to nuclear energy has also implications since it forces this industry to improve the technology in terms of safety and security.

#### *1.4 Other options*

The fact that Europe produces around 35% of its electricity with nuclear power has a positive impact on the environment. Indeed, the avoided CO<sub>2</sub> emissions correspond roughly to those emitted by the European cars. A decrease of nuclear power would have to be compensated by other production facilities. The best choice would be gas plants based on combined cycle turbines gas (CCTG). However, this would have many economical and environmental consequences. On the economical point of view, we have already said that the price of gas represents a large part of the electricity price. It is difficult to foresee the evolution of the price of gas but it is very likely that it will continue to increase in the next decades since it is closely correlated to the price of oil. On the environmental point of view, although gas is the cleanest fossil fuel, carbon dioxide is produced when it is burned. It would therefore be more difficult for Europe to fulfill the Kyoto protocol. Coal, using clean technologies, would be another solution but worse than gas as far as CO<sub>2</sub> emissions are concerned and there are also other kinds of pollution. Nevertheless, coal is the energy of the future because of its reserves extending over a few centuries. It will be possible to synthesize oil from coal (CTL). Renewable energies would of course be interesting, however, apart hydraulics, which is extensively used when it is possible, other sources like wind are intermittent and could hardly produce base-load electricity. Furthermore, the quantities of electricity which can be produced at an acceptable price could not compensate the present nuclear energy production. For example, in Germany, there was, in 2003, 14.345 GW windmills installed but only 18.6 TWh of electricity produced, corresponding to an efficiency of only 14,8% (2003 EON wind report 2004).

#### *1.5 Other potentials applications of nuclear power*

At the moment, nuclear energy is only used for electricity supply. With the progressive decrease of oil production in the near future, when the oil peak will be reached, it will be necessary to use nuclear energy for other applications.

The first one concerns transportation which depends essentially on oil. Electric vehicles will probably not be used on a large scale because of running time problems. The number of hybrid vehicles, using conventional engines burning oil and an electric engine associated to batteries, will probably increase. In the future, it will be possible to load the batteries using electricity of the grid. In such a case extra electricity would be needed and nuclear energy could play a role. Plug in hybrid vehicles with an electric range of 30-40 km are interesting because many people cover smaller distances to reach their working place. This will allow using most of the time electricity to run the car.

In the long term, hydrogen might also be a good energy vector for transport. Hydrogen will be used in fuel cells although one might also think to use it directly in conventional engines. Energy is needed to produce hydrogen from gas, coal, biomass

or water. If CO<sub>2</sub> emissions have to be avoided, the best solution is to produce hydrogen from water. The simplest way, which is still expensive, is the electrolysis process. Another way to produce hydrogen from water is thermochemical cycles. This idea is to use several intermediate chemical reactions, involving sometimes dangerous chemical products, to dissociate the water molecule and produce hydrogen. This requires temperatures of the order of 1000°C. Nuclear reactors, specifically designed to work at these very high temperatures could in principle be used. However, even if one would be able to demonstrate that such technologies work; it will remain the question of operating, in the same area, both a nuclear and a chemical plant. This is probably not a good choice for safety reasons and there will probably be a strong opposition of the neighboring population. Probably the best solution to produce hydrogen will be to perform electrolysis in decentralized stations. However, it is by no means clear that hydrogen will be a relevant fuel for transport in the near or medium future. Liquid fuel is by far more interesting in terms of energy density content and could be produced in the future through several methods (CTL, BTL, GTL).

Another interesting application of nuclear energy will be to desalinate water. This requires energy and, with nuclear power, it will be possible to produce drinkable water. However, it will remain too expensive to produce water for agriculture (watering crops).

The yield of present nuclear plant is still low, due to the Carnot principle, because the operating temperature is not high enough. This means that for each electric kWh produced, 2 kWh of heat are lost in the environment. Increasing the temperature of operation will increase the yield of electricity production. Yields of about 50% could be reached in the future. This would mean that for each kWh of electricity, only 1 kWh of heat is lost. It would be interesting to develop technologies, based on heat pumps, exploiting low temperature fluids. Right now, at the world scale, heat production for the final users ( $\approx 3$  Gtoe) is 3 times more energy than electricity ( $\approx 1$  Gtoe).

## 2. General issues on nuclear technologies

### 2.1 Peculiarities

#### 2.1.1 Risk of proliferation

A potential drawback of nuclear energy is the risk that reactors might be used to military ends, to develop nuclear weapons. That has happened, for instance, in North Korea over the last few years, although these reactors were not devoted to civil applications, and illustrates the problem of nuclear proliferation. Presently, there are also problems with Iran.

The problem of proliferation has an important impact in international diplomatic relationships. This is why experts of the AEIA (Atomic Energy International Agency) are running all around the world, to inspect and control nuclear installations. Nuclear programs in countries like Iran or Libya have also recently come under scrutiny by the world community. After Libya agreed to dismantle its embryonic weapon program, the AEIA announced that finding out whether other countries had acquired nuclear weapons technology was "an important and urgent concern for us".

There is an international treaty that limits the use of nuclear power to pacific uses. Signed in 1970, it binds on one hand countries that have tested nuclear weapons before 1967 (USA, URSS, United-Kingdom, France and China) which should not help other countries to get nuclear weapons, and, on the other hand, countries that do not have nuclear weapons and which should not try to manufacture or acquire it. Moreover, this treaty favors pacific uses of atom, by giving the right to develop research, production and peaceful applications of nuclear energy. All signatory countries commit themselves to make easier information, equipment and material exchanges, and technological and scientist cooperation. Nevertheless, exchanges of specific fissile materials are prohibited. The treaty has a clause of disarmament, under international control. The AEIA has the responsibility to control the worldwide accounting of nuclear materials and its peaceful uses. With the discovery of surreptitious nuclear activities, controls have been reinforced.

Because of the recent events, the USA have proposed several new initiatives for curbing the spread of nuclear weapons materials and expertise: countries mastering nuclear technology should not sell enrichment and reprocessing equipment to any state that does not already possess full-scale, functioning nuclear plants. Moreover, the effort to intercept potential mass destruction weapons will be increased and all nations will have to sign the IAEA "Additional Protocol", expanding the agency's authority to investigate surreptitious nuclear activities.

The Comprehensive Nuclear Test Ban Treaty (CTBT) bans all nuclear explosions for military or civilian purpose. It started to be signed in 1996. Among the 44 States of the so-called annex 2 who signed the treaty, only 33 have ratified it. There are 3 States who did not sign it. To a larger scale, 176 States have signed the treaty and 125 have ratified it. Signature and ratification are required for the treaty to enter into force.

#### 2.1.2 Reserves of Uranium

The uranium reserves are regularly evaluated by the OECD/NEA (Organization of Economic Cooperation and Development/Nuclear Energy Agency), in collaboration with the AEIA (Atomic Energy International Agency). Presently, about 3 millions of tons of natural uranium should be exploitable in the world, at a price lower than 80\$/kg. The present annual needs are estimated to 60 000 tons. If they stay at

this level, these resources could satisfy the worldwide demand during the next 50 years.

For a cost of 130\$/kg, 900 000 additional tons would be available, corresponding to 15 years of today consumption. The total stock would be about 16.9 millions tons if conventional additional resources are added (potential ones). Therefore, the reserves reach about 280 years. Uranium reserves are geographically shared between all continents and a large part are in countries which are politically stable. This ensures supply security. Furthermore, since nuclear energy is a very concentrated energy source, it is easy, for countries using this way of production, to have reserves for several years, even decades.

Because the price of natural uranium represents only a small part of the price of electricity, there is no real concern about uranium reserves for low energy neutron reactor technology. Since fast reactors will multiply these reserves by a factor greater than 100, the world has energy reserves for several tens of thousand years, even more if one considers using thorium nuclei.

Countries	Australia	Kazakhs-tan	Canada	South Africa	USA	Namibia	Brazil	Russia	Uzbekis-tan	Ukraine	U.E.	Total
K tons of uranium	930	854	436	367	348	282	262	174	172	131	62	4392
% of worldwide production	32,1	19,4	9,9	8,4	7,9	6,4	5,9	4	3,9	3	1,4	

Worldwide resources of uranium in 2001 Source CEA

Presently, mines are not the only source of uranium. Dismantling nuclear weapons and using its high-enriched uranium components permit to save, each year, 5 000 tons of natural uranium. After being used, uranium fuel can be reprocessed. A re-enrichment of depleted uranium can potentially replace 105 000 tons of natural uranium. For all these reasons, the worldwide uranium mines production was only about 35 000 tons in 2000 representing half of the nuclear reactors needs. Furthermore, electricians, especially American ones, have a lot of uranium because they have anticipated a larger number of plants than has been built. Nevertheless, a strong development of nuclear power might lead to a shortage of uranium fuel in the middle of the century. Investments in the field of uranium mines are therefore shortly required.

Uranium mines have been closed in the European Union because they were running out of the resource and had high exploration costs compared to other places which have a low market price (about 26\$/kg).

Cogema, (General Company of Nuclear Materials) is the only European producer of natural uranium. It is exploiting 20% of the worldwide production (6000/7000 tons per year, second place in the world) in Canada, Australia and Africa.

### 2.1.3 Stocks and share of nuclear fuels

Depleted uranium and reprocessed fuel can in principle be re-enriched and represent a potential source of  $^{235}\text{U}$  for thermal reactors. It is also a basic resource of  $^{238}\text{U}$  for fast reactors.

During energy production, thermal reactors produce plutonium. Typically, after 40 years of operation, the N4 reactor run by EDF has produced 11 tons of plutonium. The  $^{239}\text{Pu}$  isotope can be incorporated to the fuel used in the reactors and some of nuclear plants are allowed to burn it to produce electricity. The technology which exploits  $^{239}\text{Pu}$  is the MOX (Mixed Oxide, a mix of uranium (94%) and plutonium (6%)). It is currently used in France. In the PWR (Pressurized water reactors), 32 burn MOX fuel: 17 in France, 10 in Germany, 3 in Switzerland and 2 in Belgium. MOX fuel and reprocessed uranium rely on installations in France and United Kingdom which master these technologies.

MOX is mainly manufactured in France (Cogema produces 115t/year at Marcoule and 35t/year at Cadarache) and in Belgium (Belgonucleaire produces 35t/year at Dessel). MOX can be reprocessed. This has been demonstrated at La Hague on more than 10 tons. There are also R&D improvements in the way MOX is burned and it could be in principle reprocessed and used several times.

Low enriched uranium materials are principally in France at Cogema-Eurodif (190 Mt) and in the United-Kingdom at BNFL (30 Mt) and Urenco (16 Mt) in Germany, Netherlands and the United-Kingdom. Consequently, there is a total reserve of 236 Mt of uranium, which is stored in steel containers, in high conditions of safety.

## 2.2 *Environmental aspects*

As it is the case for all industrial sites, nuclear plants have an impact on environment and generate waste. Any spread of nuclear waste would lead to pollution and possibly strong consequences for environment and health.

A nuclear plant needs water for the cooling which is taken from the sea or a river. This water is heated and treated (demineralization and chlorination). There are two circuits in a PWR, the primary and the secondary one. The fuel rods are inside the primary coolant circuit and isolated from it. During the nuclear process, the water can become radioactive if there is a leak in the fuel rod. This radioactivity will be confined since the second circuit is isolated from the first one.

There are three kinds of impacts:

- Radioactive: liquid or gas, coming from purification, filtration
- Thermal: for the open circuit because the output water is at a higher temperature than the input one. Cooling towers may be necessary if the river flow is not enough to cool the nuclear plant.
- Chemical: sodium, chlorides, sulfates

Most part of effluents is reused, and return in plant circuits after cleaning. The part that is not reused is stored and treated before it is taken care of.

In Europe, nuclear electricity avoids the emission of about 500 million tons per CO<sub>2</sub> a year. This is a very positive point in view of the global warming problem.

It is necessary to have a global approach in order to assess the environmental impact of nuclear power. In particular, in looking carefully at the dioxide emissions one should also consider all the other stages of this industry: building nuclear plant (concrete as well as other materials), transportation, enrichment of uranium, manufacturing of fuel rods, reprocessing and so on. All these stages require energy and emit more or less greenhouse gases. After running 3 months, a nuclear plant has produced enough energy to compensate its construction. The plant has also offsets the carbon emissions by generating electricity without CO<sub>2</sub> emissions. Nuclear power also does not emit sulfur dioxide SO<sub>2</sub> and oxide nitrogen NO<sub>x</sub> which are responsible for acid rains.

A minutely monitoring of aquatic surroundings has also shown that the balance of ecosystem is preserved.

### 2.2.1 Safety

The nuclear industry in Europe is strictly regulated and has excellent safety results. Safety is the industry's top priority. These safety results have been achieved by high standards applied to the design, maintenance, and operation of nuclear installations (power stations, nuclear fuel manufacturing, reprocessing plants and various installations needed for processing and storage of radioactive waste). Research and development have played a key role in this respect. As far as nuclear plants are concerned, a detailed periodic safety review is made every ten years.

The safety of a nuclear plant has to be made within an industrial context, with economic constraints, complexity, geographical dispersion and sometimes significant inertia. In countries like France, where a major part of electricity production is made from nuclear power, safety is a very important concern since any stop in the plants due to safety reasons would be an economic disaster. That is the reason why rigorous rules are applied.

Nuclear energy has, for a long time, recorded any incident occurring in nuclear plant and classified it according to its importance.. The French Higher Council of Safety and Information Nuclear (CSSIN) was at the origin of the international scale of the INES (International Nuclear Event Scale), adopted in 1994. Its activity applies to all the installations controlled by the Authority of nuclear safety. In its principles, the INES scale comprises 8 levels (from 0 to 7), level 7 corresponding to a major accident such as Chernobyl. Recording any incident has the advantage of making a data base which allows improving everyday safety since the past

experience is taken into account thoroughly. Any minor incident is recorded, even if it has no consequence on the nuclear system.

### 2.2.2 Waste management

The amount of radioactive waste generated annually by nuclear power plants is small compared with the total volume of waste produced by modern industrialized society. In France, for example, there are about 3 500 kg of waste per inhabitant and per year. Among them, about 100 kg are toxic. The amount of conditioned nuclear waste produced to get about 80% of the French electricity is of the order of 1 kg per inhabitant and per year. Among this, about 100g should be looked at very carefully because they have a long life time.

Part of the cost per kWh is set aside by the operator to finance management of nuclear waste. There exist already scientific and technological solutions to manage nuclear waste but still no political choice among them. It turns out that quite a lot of experience exists about nuclear energy in many European countries. But the management and disposal of high-level radioactive spent fuel is tricky problem all around the world because it involves an acceptability of the society which is not at all established in many cases. At any rate, it seems that a reversible storage solution is required.

It turns out that a deep underground disposal is probably the best option. The basic technology and financing mechanisms are already in place for that. Building up political consensus and public acceptance should now be the top priority, in order to achieve further progress in this area. Significant progress has already been made in Finland or Sweden, with always the idea of reversibility of the solution.

### 2.2.3 About waste: what, when, how?

When nuclear fuel is removed from a reactor after being burned, there are two opposite strategies.

The first one is to keep the used fuel as it is and consider the whole as a waste. This is the choice done by the United States. The reason for that is essentially preventing proliferation of nuclear materials. The volumes of nuclear waste make things to change in the USA and reprocessing seems to receive now some attention.

The second one is to reprocess the spent fuel in order to separate materials which could be used again, from those which should be considered as final waste. Indeed, in used nuclear fuel, most of the components are valuable. There is 93-94% of uranium and 1% of plutonium which can be used in the future or in MOX fuels for plutonium. There are about 3-4% of fission products which can be considered as final waste and less than 0.1% of actinide nuclei. Part of the latter could possibly be incinerated in fast reactors, or in dedicated nuclear facilities (accelerator driven systems), but there will still remain some final actinide waste.

#### 2.2.4 Reprocessing

Spent fuel is kept in safe place waiting for a strong decrease of radioactivity and before reprocessing. Reprocessing is carried out by two major companies, BNFL in the UK and Cogema in France. It allows recovering about 97% of the reusable material contained in the spent fuel. Plutonium can be used in the production of mixed oxide (MOX) fuel. The remaining 3% are highly radioactive or long life time nuclei. Part of them will have a radioactive activity low enough within the next 200 years while a small part will still remain active beyond that time. The waste can be immobilized in glass blocks (so-called vitrification process) and encased in special stainless steel containers for interim storage in dedicated facilities. At a later stage, vitrified waste can be disposed of in deep underground repositories.

In Europe, only France, Belgium, Switzerland, Netherlands, UK and Germany have chosen to reprocess nuclear waste, mainly at La Hague (France).

#### 2.2.5 Dismantling

The life time of a nuclear plant is determined by the vessel and the containment which may become too fragile. Techniques are already in use for a safe decommissioning of nuclear facilities and a restoration of nuclear sites.

There are 4 big parts in a site:

- The civil engineering structure
- The control command system
- The steam generator, turbo-alternator
- The nuclear boiler

The 3 first elements can be transformed or replaced but not the last one, which determines the real life time of the nuclear reactor.

A typical dismantling should take about 25 years in 3 steps:

- Definitive stop and discharging nuclear fuel, all circuits being definitively stopped
- Partial dismantling: removing the nuclear building and the confinement of nuclear sector
- Total dismantling to reach a situation where the land can be used safely for other purposes.

Dismantling will lead to about 600 000 t of non radioactive waste, and 200 000 t of nuclear waste. It turns out that actual decommissioning costs are smaller than originally expected, thanks to technological advances and to the accumulation and sharing of technical know-how and data.

The European nuclear industry has companies that are world leaders in the huge global market of plant decommissioning and site restoration. Dismantling costs

should represent about 15% of building cost and correspond to quite a lot of employment.

### 3. Description of nuclear technologies

#### 3.1 Nuclear Fission

Almost all the nuclear reactors operated in the world are thermal nuclear reactors in which fission of  $^{235}\text{U}$  nuclei is used to produce energy. Even for this type of reactors, there are several families able to produce energy. In the future, it will be necessary to use fast reactors that can also use  $^{238}\text{U}$  and transform it in a useful nuclear fuel. The advantage of fast neutron reactor technology is that the reserves of fuel available for nuclear fission are multiplied by a factor larger than 100.

##### 3.1.1 Characteristics of a thermal nuclear plant

A nuclear plant is characterized by 3 elements:

- Fuel, containing uranium nuclei which will fission and liberate energy
- A moderator which thermalizes the neutrons emitted by the fission process. In slow neutron reactors, one uses the fact that thermal neutrons have a very large capture and fission cross section for  $^{235}\text{U}$  nuclei. On the other hand these neutrons cannot fission the  $^{238}\text{U}$  isotope. There are, in the average, 2.5 neutrons emitted during the fission process. Most of them are lost or captured and there remain of the order of 1 neutron in order that the chain reaction continues but do not diverge. Most of the neutrons are emitted promptly after the fission process occurs. Fortunately, a small number of them is a bit delayed which allows to control the chain reaction and avoid divergence. These delayed neutrons are the key point to exploit nuclear energy. When other fissile nuclei are used, this number may be too small, or the delayed period too short, making more difficult to control the reactor.
- A coolant which cools the core of the reactor and extract the produced heat

These elements vary with reactors types. Their combination defines the technology of a nuclear plant. In Europe, there are 4 types of technologies:

Technology	Type	Fuel	Moderator	Coolant
Graphite Gas	AGR (Advanced Gas Reactor) HTR (High Temperature Reactor)	Enriched uranium Natural uranium or thorium	Graphite	Carbonic gas or Helium
Heavy Water Reactor	PHWR	Natural uranium	Heavy water	Heavy or ordinary water, or organic liquid
Light Water Reactor	BWR (Boiling Water Reactor) PWR (Pressurized Water Reactor) WWER	Enriched uranium	Ordinary water	Ordinary water
Fast Breeder Reactor		Plutonium	Not necessary	Sodium

Nuclear reactors have a lot of elements:

- Control rods, which absorb neutrons to control or stop the reaction
- Fuel assemblies, containing fuel pellets
- Core, reactor vessel in pressurized steel
- Primary and secondary circuits
- Steam generator, pressurizer
- Cooling system
- Containment structure, with concrete shield, to protect the core and avoid radiations
- Motor pump, turbine

There are 3 safety barriers to protect a PWR reactor against any incident:

- 1<sup>st</sup> the tube around fuel pellets (fuel rod)
- 2<sup>nd</sup> the envelope of the primary circuit, including the reactor pressure vessel which is made out of steel
- 3<sup>rd</sup> the containment structure of the reactor made out of concrete of 1 meter thick

France is producing its electricity with PWR reactors with power ranging from 900 to 1450 MW. A nuclear reactor can typically develop a power from 400 MW (first generation) to 1600 MW (EPR, Generation III+). There are between 2 and 6 nuclear reactors in each producing electricity site.

### 3.1.2 Availability

The availability represents the fraction of time during which the nuclear plant produces electricity. It is below 100%, because shutdowns are necessary for refueling and safety reviews. It varies from 78% to 83% in practice but technically,

the availability could be over 90%. The difference is partly due to an increased security and to prevent ageing. An increase of the availability allows reducing the number of production unit. For example, in the United States, the electricity production due to nuclear plant has increased despite a decrease of the total number of nuclear reactors. This is just due to an increase of the availability time production.

### 3.1.3 Outage for refueling operations and safety review

Shutting down a nuclear reactor requires a good schedule:

- The shutdowns have to be chosen while taking care of the required production of the whole electricity system. The operating period, which structures the activity of the park, is from 18 months to 5 years, and defines the fuels needs.
- It is also an economical problem since one needs to minimize the fuel expenditures, by exploiting variations of demand during summer and winter
- It is a task organization problem taking into account the multiplicity of constraints concerning availability of plants.

Stop for refueling happens every 12 or 18 months. This halt is lasting, in average, about 44 days, but there are others which are longer when necessary:

Average Power	Stop to refueling	Milestone safety review	Decennial safety review
900 MWe	41 days	55 days	90 days
1 300 MWe	47 days	63 days	100 days

Source: EDF

There are also milestone safety reviews and, every ten years a decennial safety review which is more detailed.

### 3.1.4 Flexibility of a nuclear plant:

It is difficult to store large quantities of electricity and the supply should balance the demand. This means that there should be some flexibility in the supply. In this respect, nuclear plants are not the most appropriate tool but a lot of progress has been done. The time of reactivity, to follow the demand, is 30MW/mn for a 900MW reactor and 40MW/mn for a 1300MW. The technical minimum is 25% of the net continuous power. There should be no more than 1 stop and go per 24 or 72 hours. The primary reserve is 2% while the secondary one is 5%.

### 3.1.5 Lifetime of nuclear reactors

The capability of plants to have a long lifetime is conceivable with appropriated maintenance, and by bringing the installation at the required standards. The stake is serious in terms of competitiveness and environmental impact. French reactors, for example, were designed for 30 years but it turns out that their life-span could be extended to 40 years. New reactors are designed for 50-60 years. All nuclear countries are making important R&D efforts about the ageing of materials, especially about non-replaceable elements. In that respect, the AEIA is working along 3 lines: improving safety rules, synthesize R&D results and writing advices.

### 3.1.6 Energy contained in enriched uranium

Enriched uranium for PWR has an energy of 3900 GJ/kg corresponding to 86,000 times the energy contained in oil (45 MJ/kg). It is 100 000 times more than gas (39MJ/kg) and 156 000 times more than coal (25MJ/kg in average).

## 3.2 Nuclear fuel

### 3.2.1 Enrichment of uranium

Uranium ore is not rare. It is extracted from mines via open-pit mining or leach mining. The raw ore is milled and chemically leached. The resulting powder is called "yellow cake". The yellow cake powder is converted to uranium hexafluoride  $UF_6$ , which is used for enrichment.

Natural uranium does not contain enough of the fissile uranium 235 isotope ( $^{235}U$ ) to sustain fission in PWR's. Indeed there is only 0.7% of  $^{235}U$ , the only one thermal neutron fissile isotopes, and 99.3% of  $^{238}U$  in natural uranium. The nuclear fuel used in PWR is enriched to about 4 % and 5% of  $^{235}U$ .

There are two processes of enrichment.

The first one is the gaseous diffusion enrichment process. It has been developed in the USA and in France. It is the oldest industrial technique. It uses the difference in atomic mass between the two uranium isotopes  $^{235}U$  and  $^{238}U$ .

The isotopes are partly separated in a diffusion stage. The gas is pumped through porous tubes called diffusion barriers by a compressor. Because the enrichment coefficient is low, the process is repeated 1,400 times to achieve the uranium 235 required enrichment. This enrichment method requires a lot of energy and is becoming now less competitive.

In the European Union, Eurodif plant has been enriching uranium for close to 100 nuclear reactors in France and around the world since 1979. The EURODIF Production plant, called Georges Besse plant, is located at the Tricastin nuclear site in Pierrelatte, France. It represents 23% of the world enrichment capacity, with 10,8 MSWUs. Four nuclear reactors are close by and dedicated to provide

electricity to this diffusion plant although they are not all working at the same time.

The second method is the centrifugation process. It consists in rotating at high velocity the  $UF_6$  in centrifuges. This allows separating uranium 235 and uranium 238, thanks to the mass difference of the isotopes. The centrifugal forces push the heavier  $^{238}UF_6$  closer to the wall of the rotor than the lighter  $^{235}UF_6$ . The gas closer to the wall becomes depleted in  $^{235}U$  whereas the gas nearer the rotor axis is slightly enriched in  $^{235}U$ .

The enrichment level achieved by a single centrifuge is insufficient to obtain the needed concentration of  $^{235}U$ . It is therefore necessary to cascade several tens of centrifuges together. Passing through the successive centrifuges of the cascade, the  $^{235}U$  is gradually enriched to the required assay, typically between 3 and 5 %. Thousands of such centrifuges are necessary for a significant throughput.

The specialist of this process is the European consortium Urenco (United Kingdom, Germany, and Netherlands), with 3 sites of production: Gronau in Germany; since 1985, Almelo in the Netherlands, since 1972, and Capenhurst, in U.K., since 1976. This consortium represents 11% of world enrichment capacity with 5,3 MSWUs.

The rest of enrichment capacities is in USA (24%/11,3MTUS), using gaseous diffusion, and Russia (11%/20MTUS), based on centrifugation.

The Separative Work Units (SWUs) are a measure of the amount of effort required to separate the  $UF_6$ , in order that the product stream is enriched and has a higher percentage, of  $^{235}U$ . This is calculated using a standard formula. The higher the  $^{235}U$  concentration, the more SWUs are required.

### *3.3 Future Nuclear Technologies.*

Within the next thirty years, thermal neutron technologies will still be the relevant technology to be used. Fast reactors are for a longer term although research and development should be carried out during this period in order that Europe be ready and competitive when they will be needed. During this period, the new EPR (European pressurized reactor) is a key technology to replace or to build new facilities.

#### 3.3.1 EPR

This new evolutionary reactor is more powerful than those of Generation III: 1 600 MW. Its design is based on experience feedback from several thousand reactors×years of light water reactor operated worldwide.

There are a number of safety innovations to prevent core meltdown and mitigate any potential consequence. It has also been designed to better resist to external hazards like airplane crashes or earthquakes. The reactor core is flexible in terms of fuel management, especially as far as MOX is concerned. It allows saving 17% on

the uranium consumption and reducing 15% of long life time actinides per MWh produced. The thermal power range between 4,25 and 4,6 GW and the electric yield is 36%. The burn up is larger than 60 GWd/t. The probability of serious accident has been divided by a factor ten compared to the present technology which is already very safe. One of the consequences of this enhancement of safety is that no evacuation of more than one year beyond 800 meters of the reactor should be necessary in case of a serious accident.

The life-span for the non replaceable components will be 60 years and the availability 91%, thanks to refueling periods reduced to 16 days instead of 44 in average, and a fuel cycle from 18 to 24 months.

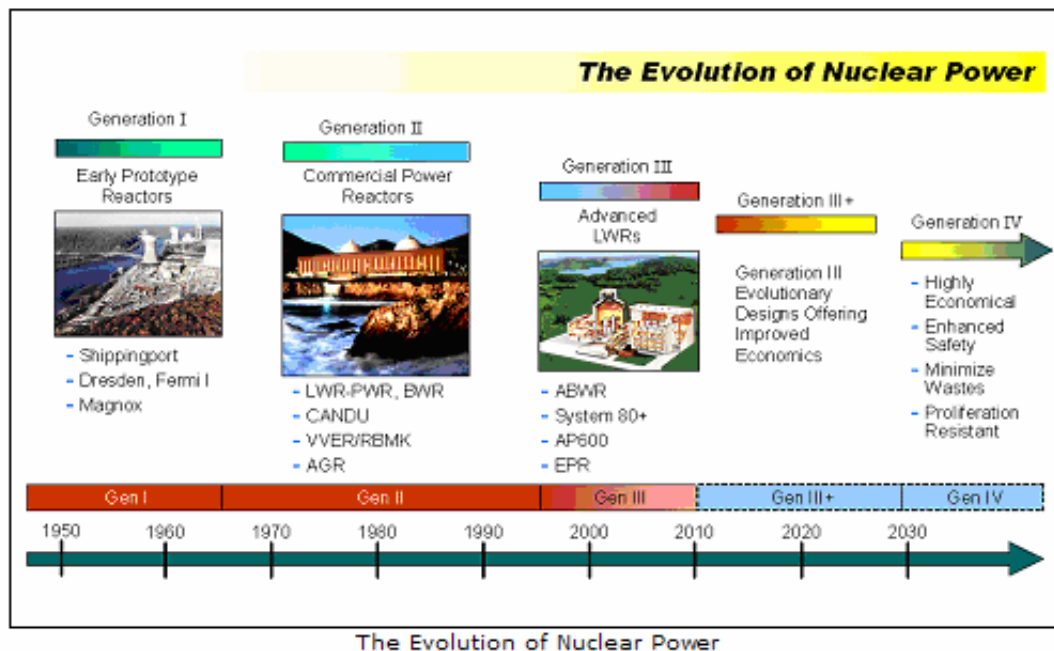
Two EPR will be shortly built in Europe: one in Finland and one in France.

### 3.3.2 Generation IV

The aims of the generation IV reactors are: saving natural resources, a higher profitability, a reinforced safety, a reduction of high-level waste, the possibility to use nuclear power for other applications than the one of producing electricity. Studies are made within an international cooperation involving many partners. The scientific and technical researches will be at the international level.

The Generation IV International Forum (GIF) has selected six options, divided in four concepts:

	Spectrum	Fuel cycle	Power(Mw <sub>e</sub> )
<i>1.Light water reactor</i> Super Critical Water Cooled Reactor (SCWR)	Thermal/Fast	Open/Closed	1500
<i>2.Very high temperature reactor with gas coolant</i> Very High Temperature Reactor (VHTR)	Thermal	Open	600
<i>3.Fast neutrons reactor</i> Sodium Cooled Fast Reactor (SFR) Gas-Cooled Fast Reactor (GFR) Lead Alloy-Cooled Reactor (LFR)	Fast Fast Fast	Closed Closed Closed	150-500 288 120-400
<i>4.Molten salt reactor</i> Molten Salt Reactor (MSR)	Thermal	Closed	1000



Closing of the nuclear fuel cycle will be determining. An opened cycle, without reprocessing, has to store the spent fuel as it goes out from the nuclear reactor. A closed cycle permits to reprocess the used fuel by separating its components to be used later on. The first units will probably be commercialized around 2040-2050.

### 3.3.3 Innovative ideas

Until now, nuclear energy has been used almost exclusively to generate electricity, but it has other possible applications. Energy is also needed to produce heat (domestic hot water and heating) and for transport. Therefore, it would be interesting to extend the possibilities of a nuclear reactor in order to contribute also to these other applications.

The thermal nuclear reactors used presently are such that for 1 kWh of electricity produced, there are 2 kWh of heat released in the environment. Developing high temperature nuclear reactors, with a yield of 50% would be interesting since, roughly speaking, for each kWh of electricity produced, one would only release 1 kWh of heat in the environment. Research is done in this direction.

As far as high temperature heat production is concerned, large quantity of heat will be needed to exploit non conventional oil, like tar sands or oil shale. Small nuclear reactors producing heat to extract these resources would be interesting.

A large part of heat produce in the world is at moderate temperature for domestic use and heating homes. In the future, it might be interesting to transport water taken downstream the nuclear or fossil fuel plant, where the temperature is higher than upstream, to nearby cities and back. The low temperature water can then be upgraded to 60-70°C using heat pumps and the produced heat supplied to dedicated

networks for home heating. This would require large investments but that would probably be competitive as the price of oil and gas increases.

In the future, hydrogen could be an interesting energy vector. Unfortunately H<sub>2</sub> does not exist on the earth and should be produced either from fossil fuels (gas or oil), or from water. Nowadays, a large part of hydrogen is obtained from gas. In the future, it will be necessary to produce it from water by methods which do not emit greenhouse gases, which is not the case with natural gas. The more straightforward method is to use water electrolysis. This would require carbon free production of electricity. Renewable and nuclear energies can do that. Therefore, more electricity would be needed to produce hydrogen. This energy vector could be used in stationary applications using high temperature fuel cells to produce electricity and heat. It can also be used in the long future for transport (cars, trucks, buses, etc.) using low temperature fuel cells. Another possibility to produce hydrogen, as quoted already above, is to use thermochemical cycles. This would require very high temperature nuclear reactors. These are already tricky to design because materials resisting at very high temperature are needed. However, the main problem will be safety and social acceptability because it is unlikely that any European population would accept to have a chemical unit and a nuclear reactor at the same place.

Hydrogen is also necessary in petrochemistry to convert heavy oil fractions into light products by cracking and hydrogenation

There will probably be more and more hybrid vehicles in the next decades which combine an internal combustion engine to an electric one and a battery. In the future, it will probably be possible to charge the battery on the electricity grid. This will require extra electricity.

To give an order of magnitude of the energy needed for transportation, let us consider France as an illustration. The electricity consumed per year is about 450 TWh. The energy needed for transportation is of the order of 500 TWh. In addition, the energy needed to produce heat is between 2 and 3 times that of electricity. This means that nuclear energy, as well as renewable energies, are good candidates to decrease our demand in fossil fuels. The needs are large and will require new and important new units of production.

Another potential application of nuclear energy is the desalination of sea water.

## 4. Present Nuclear Fission Market

### 4.1 *Nuclear fission in Europe*

There are 13 countries in European Union which use nuclear technology to produce electricity.

The 155 European reactors are producing about 35% of all the Community's electricity. They are, in the average, 21 years old. The PWR is the most widespread technology. Moreover, 57 reactors have been shut down, representing a power about 14 500 MW. Nuclear is the European Union largest single energy source of electricity with 33% of generation, ahead of coal (29%) and gas (15%). It produces large amount of electricity at competitive price and operates reliably, without emitting greenhouse gas.

#### *4.2 Costs*

The structure of nuclear electricity production costs is particular compared to other sources of production. Fixed costs represent 85% of the total and variable costs only 15%. Nuclear energy is characterized by large investment costs. This is similar to renewable energies for private individuals. For fossil fuels plants, this is the contrary although this should not be very different if the investment of transport and storage facilities are taken into account.

#### *4.3 Fuel cost*

Supplying nuclear fuel depends on management method, and represents, in average, about 20% of the cost of electricity, but natural uranium represents only 5% of the global cost (OCDE 2002). Therefore 95 % of the cost includes fuel manufacturing, exploitation of the plant exploitation and maintenance, and paying off investments. However, one of the main advantages is that the price of electricity remains stable even if the price of natural uranium increases a lot (see above). For example, the price of  $U_3O_8$  has increase by 300% in 2 years (from January 2003 to summer 2005) without any visible consequence on the price of the produced kWh.

Countries	Number of reactors	Net Capacity (MW)	Production/year (GWh)	Share of total electricity generation (%)	Type	Cumulative Net Load Factor (%)	Construction start (first / last reactor)
France	59	63 300	420 760	77,9	PWR	71	1972 / 1991
Germany	18	20 640	157 440	28,1	BWR PWR	73 83	1965 / 1982
United Kingdom	27	12 050	88 043	22,7	AGR CGR PWR	67 74 80	1955 / 1980
Sweden	11	9 430	65 500	49,6	BWR PWR	75 70	1966 / 1979
Spain	9	7 570	59 360	23,6	BWR PWR	81 82	1964 / 1975
Belgium	7	5 760	44 610	55,5	PWR	89	1969 / 1978
Czech Republic	6	3 460	25 870	31,1	WWER	80	1979 / 1987
Slovak Republic	6	2 400	17 860	57,4	WWER	75	1974 / 1983
Finland	4	2 650	21 820	27,3	BWR WWER	92 86	1971 / 1975
Hungary	4	1 750	11 010	32,7	WWER	86	1974 / 1979
Lithuania	2	2 370	14 300	79,9	LWGR	55	1977 / 1978
Slovenia	1	670	4 960	40,5	PWR	79	1975
Netherlands	1	450	3 800	4	PWR	81	1969
European Union	155	132 000	935 33	33,1			

Source CEA Elecnucl 2004

Total fuels costs take care of the whole nuclear fuel cycle:

- Front-end: purchase and manufacturing uranium in  $U_3O_8$  form, conversion to  $UF_4/UF_6$ , enrichment, manufacturing fuel rods
- Period where the fuel is burned in the reactor
- Back-end: transport to factory or temporary storage, reprocessing and conditioning, transport to definitive storage

Uranium used in nuclear fuel is available from various countries which have a long history of political stability. This includes in particular Australia and Canada. This has a stabilizing effect on uranium prices and supply. Anyway, any rise in uranium prices would have only a minor impact on the costs of nuclear electricity. Power plants that burn fossils are more fuel-intensive; producers and consumers therefore face a greater risk of increased costs due to higher fuel prices. In a gas

plant, for instance, the price of the gas enters for about 70% in the price of the electricity produced.

#### 4.3.1 Cost of the kWh

If we consider the following situation for the EPR: 60 years of life-span, 10 units built in series, 90% of availability; then the cost of the kWh on base load generation is shared in the following way:

Fuel	15%	4,4€
Investment	58%	16,3€
Running	18%	5,1€
Taxes	7%	2€
R&D	2%	0,6€
Total	100%	28,4€

Source Dideme 2003

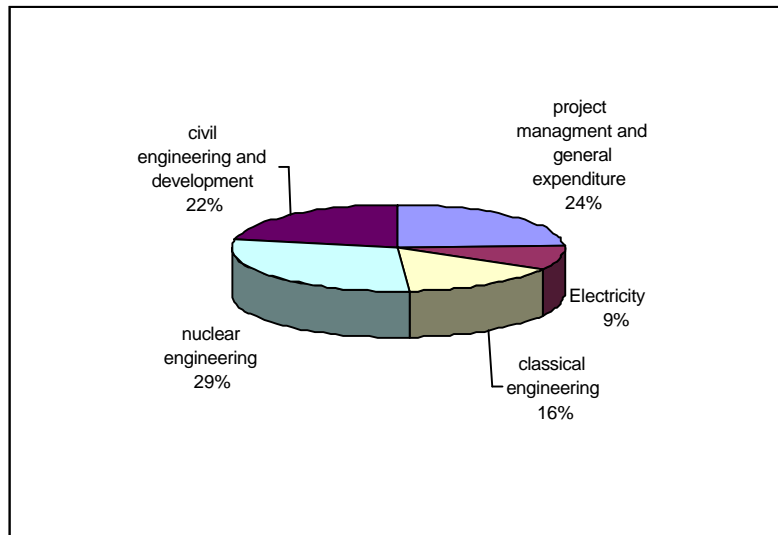
In European Union, the MWh ranges between 22 and 32 €.

The external costs are the lower of the energy industry. The costs like environmental and health impacts, dismantling of plants, and the very small CO<sub>2</sub> emissions (around 4-6g/kWh) are between 2 and 7 € (ExternE study). This leads to a total cost ranging from 24 to 39€/MWh. Exploitation and maintenance represent from 15 % to 20 % of the nuclear kWh cost.

The external costs are the lower of the energy industry. The costs

#### 4.3.2 Investment cost

Investment cost is the most important item of the nuclear kWh generation cost. In the average, for the Generation II PWR, the cost of kWh is 1270€/kW, broken up as indicated in the figure.



For EPR, with an up-dating rate up of 8%, it is 1663 €(2001)/kW. However, it is depending on the building program. In 2006, the latest evaluation turns out to be

about 1800 €/kW. Dismantling costs are expected to represent about 15 % of initial investment.

It is important to note that the nuclear investment is large and building the plant is quite long. This is slowed down because a lot of administrative authorizations are required. Because of that, the level of the up-dating rate has a large influence on the calculations.

## 5. Future development

### *5.1 Global European outlook*

The construction of two new nuclear reactors, in Finland and France, shows an interest with respect to nuclear power. In other European countries, many nuclear power plants will reach the end of their expected lifetime at about the middle of the next decade. It is therefore essential to be prepared, with reliable nuclear plants, to replace them. Indeed, we are faced with fighting against greenhouse emissions and satisfying an increasing demand of electricity. Nuclear power is one of the solutions to satisfy the commitments to reduce the production of CO<sub>2</sub> emissions.

In the European Union, Sweden committed to a phase out of nuclear power in 1980 after a national referendum, and has confirmed the decision to stop the unit 2 of the Barsebäck nuclear plant by the end of May 2005. However, because of the lack of replacement solution by other energy sources which are not emitting greenhouse gases, the final decision is not yet taken. Both Italy and Austria have abandoned nuclear power entirely. Belgium, Germany and the Netherlands have committed to a gradual phase-out of their programs, although in some cases such commitments have proven difficult to be carried through.

On the contrary, Finland has decided to invest in nuclear power in 2003, and a new EPR plant is under construction, the first new one in Europe since 1991. If Lithuania has closed, in accordance with his commitments, the first unit of the Ignalina nuclear plant in 2004, it intends to stay a nuclear country. Bulgaria, which will enter in E.U. by 2007, has announced the building of one nuclear plant at Běléné, on the Danube, which will be commissioned in 2010, and Slovakia is building 2 reactors, for a total power about 770MW.

Thus, given the short periodic changes in political leadership that can change official government positions on nuclear power, it is difficult to assess the degree to which current commitments for or against nuclear power will be maintained. The climate changes due to greenhouse gas emission and the oil peak which will be reached in the next decades may change many things in the energy domain and probably favor nuclear and renewable energies.

## 5.2 Forecasts

Prospects for nuclear power have improved in recent years, with higher utilization rates reported for many existing nuclear facilities and the expectation that most existing plants will be allowed to run for a longer time. Furthermore, increasing fossil fuel prices and the application of the Kyoto Protocol are expected to improve prospects for new nuclear power capacity in the near future. Nevertheless, it is difficult to quantitatively anticipate about nuclear power for a variety of political and social reasons. A lack of oil and the increasing energy dependency of European Union might nevertheless be in favor of the development of nuclear power.

## 5.3 Historical evolution of nuclear technology

Since the beginning of nuclear power, a lot of progress and evolutions have been made. In 1950, the early prototype reactors called Generation I, were built, until 1970. In 1970, the Generation II has appeared and commercial power reactors deployed all around the world (LWR, BWR, CANDU, RBMK, VVER). We are now in the Generation III, with advanced LWRs (Light Water Reactors). The Generation III+ corresponds to evolutionary reactors, with improved design and economy, like the EPR in Europe or the ABWR. This Generation is to a near-term deployment of nuclear energy. Generation IV is expected for 2040/2050. These reactors should be economical, safe, with minimal waste production and prevent nuclear proliferation. Their great advantage, as fast reactors are concerned, will be a better use of uranium resources with several tens of thousands of years of reserves. In that respect, they are in the path of a sustainable development.

# 6. Conclusion

The best solution to produce clean electricity is hydraulics when it is possible. That should be the first choice and this has been extensively done in the past. For example, in France, hydraulics was supplying 56% of the electricity in 1960. An increasing demand has led to the development of other sources. Nuclear energy is one of them and plays a key role in Europe. The future of nuclear industry depends upon the European regions. It is not the only solution to produce electricity but it can do it at a low cost and at a price which stay stable during several decades. Apart from social acceptance, nuclear energy depends very much on the economical approach of the country. If the country has a completely liberal approach, gas plants is certainly a good choice because the initial investment is small and they can be built quickly. On the other hand the price of the gas is a large part of the price of electricity and the cost of the kWh may vary a lot, depending upon the price of the gas. The shareholders have benefit at a short scale and these will increase with the price of gas. On the other hand, nuclear power is interesting in a country taking care of its people. Indeed, the price of electricity will be low and stable in time. However the initial investment is large. In this respect, nuclear energy is quite

similar to renewable energies where the initial investment is large for individuals but the running cost low. On top of this there is the problem of the rarefaction of oil and later of gas, and of the greenhouse gas emission. That leaves only few degrees of freedom to choose the good sources of energy and to decrease our dependency with respect to oil. The proper solution will be an energetic mix and nuclear energy will be one part of this energy mix.

## 7. Bibliography and web sites

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Mit study of the future of nuclear power

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C.Bataille et C.Birraux

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