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New Energy Externalities Developments for Sustainability

INTEGRATED PROJECT

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Sub-priority 6.1.3.2.5: Socio-economic tools and concepts for energy strategy.

D 14.2 – RS 1a

"Final report on technical data, costs and life cycle inventories of nuclear power plants"

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CO	Confidential, only for members of the consortium (including the Commission Services)	

Executive Summary

This document is a technology roadmap of the development of nuclear energy for the purposes of the NEEDS project (New Energy Externalities Developments for Sustainability).

On the basis of a technology roadmap featuring three scenarios, it aims at describing the types of nuclear power plant (NPP) and associated systems that are studied in NEEDS RS 1a WP 14 for the reference years (2000, 2025, 2050). These systems have to be representative of plants that would be **chosen for new build** at the considered years (2000, 2025, 2050). In fact, **in the whole report, the considered years refer to the starting date of Commercial Operation for the plant (COD).**

The aim of this work is then to collect economic and environmental data on the reference systems at the chosen years, in order to feed the databases that are requested for the global energy scenarios modelling within the NEEDS project. In addition, Life Cycle Inventory (LCI) data are provided for each of the reference technologies.

Contents of the roadmap

The roadmap describes the principles of both nuclear energy generation and nuclear fuel cycle, which is fundamental for a life cycle approach of environmental impacts.

Past and future developments of nuclear energy are described, especially ongoing research on future Generation IV nuclear in the GIF - Generation IV International Forum.

Reasonings on the place of nuclear energy in the future energy mix are based on a scenario approach, with drivers such as the relative competitiveness of nuclear energy *vs.* other energy production technologies (parameters such as fossil fuel prices, efforts for climate change mitigation), and the availability and price of uranium resources.

The task for this paper consists in defining three scenarios that are to be called "pessimistic / realistically optimistic / very optimistic", according to the general instructions for RS 1a.

We will define these scenarios as follows:

- pessimistic → stagnation or decrease of nuclear energy worldwide;
- realistically optimistic → increase of nuclear energy to 1500 GW of installed capacity in 2050;
- very optimistic → increase to 2500 GW in 2050, which seems unrealistic to us.

For each reference year, LCI data are provided that aim at being representative for the state of the art or the “best available technology” within the European fleet. It results in the choice of three milestone technologies (see below).

Reference systems at years 2000, 2025, 2050

The reference system for year 2000 is a PWR as it is described in international LCA databases: “PWR 1000 MW “, associated to a fuel enrichment by gaseous diffusion.

The reference system for year 2025 is an EPR, associated to a fuel enrichment by ultracentrifugation.

2025 is quite straightforward with evolutionary concepts, but, according to scenarios, 2050 can be the scene for diverse options regarding nuclear systems, such as:

- in the case of the pessimistic scenario: no Generation IV at all – evolutionary systems chosen for new plants in 2050;
- in other cases, tensions can occur on uranium resources, that would lead to the emergence of breeder reactors of Generation IV.

The reactor that has been chosen for 2050 is a Sodium Fast Reactor (SFR). In fact, thanks to both the EFR[1] project, and a collection of environmental data on the SuperPhenix plant, accurate data are available for a cost analysis and a Life Cycle Inventory (LCI[2]) of such reactors – which is not the case for other Generation IV concepts.

NB: Nuclear experts are neither unanimous on these future perspectives, nor on the associated drivers. Therefore, this document attempts to reflect the diversity of points of views, and to be pragmatic in the conclusions too.

The reference technologies are specified in Table 11 of this document for each scenario-year combination as needed for RS1a purposes of the NEEDS project.

Costs of reference nuclear systems

Reference costs presented in this document are levelised costs, on the basis of published literature.

The discount rate chosen for the nuclear roadmap in NEEDS is 6 %, and the currency is € 2000. We assume that the costs do not evolve over the years.

For year 2000, on the basis of reference costs [DGEMP 1997] related to a PWR of N4 type, the levelised cost of generating electricity (LCOGE) is 27 €/MWh (cf. Table 4).

For year 2025, on the basis of reference costs [DGEMP 2003] related to an EPR, the levelised cost of generating electricity (LCOGE) is 24,4 €/MWh (cf. Table 9).

For year 2050, the LCOGE of the EPR are calculated with the same assumptions as above, except for uranium which is considered to be much more expensive. In this case, the LCOGE for an EPR in 2050 would be 30.5 €/MWh (cf. Table 10, first column).

For year 2050 again, a pre-Generation IV fast breeder reactor (FBR) would have a LCOGE of 27.5 €/MWh (cf. Table 10, second column), with the following assumptions: fuel cycle cost 3.85 €/MWh (ibid.), investment cost 30 % above the EPR investment cost.

With optimistic assumptions on the goals of Generation IV, that aim at an investment cost equal to the EPR investment cost, we reach an LCOGE of 22.9 € /MWh (cf. Table 10, third column).

Life Cycle Inventory data

Quality and relevance of the data represent the main criteria of selection for this study, as essential conditions of the consistency of the LCA results. All the selected data can be assumed to be representative for other nuclear reactors of the same class in Europe as regards the LCA approach.

For year 2000, the Swiss ecoinvent database was chosen insofar as it represents the best available public LCA database. The LCI analysis of PWR highlights the predominance of the fuel step, including especially mining and enrichment, in the contribution to the emissions of key pollutants (CO_2, CH_4, NO_x,NMVOC, Radon-222 and SO_2), except for pollutants directly emitted by nuclear power plant (such as Carbon-14 and Iodine-129).

For year 2025, the study system is a PWR of EPR type in a nuclear fuel cycle involving only centrifugation. The collected data correspond to the French EPR project in Flamanville as far as possible. When missing, some data were extracted from the Swiss ecoinvent database. Like the PWR, the LCI results show the fuel step as the main contributor to the emissions of key pollutants.

For 2050, the European Fast Reactor (EFR) was retained as a satisfying representative of Sodium-Cooled Fast Reactors (SFRs). No data were directly available for the LCI study at this preliminary stage. A specific work was done on the data for EFR, with EDF experts involved in the Superphenix

[1] *European Fast Reactor*

[2] *In NEEDS only the LCI part of LCA (ISO 14040) is addressed, for impacts are estimated using external costs. That is to say, the work performed within this task will be the first part of LCA, without going as far as analysing the results.*

project. Where missing, data were extracted from the ecoinvent database. Contrary to the previous two cases, the LCI results reveal that the fuel step is a marginal contributor to the emissions of key pollutants. This is not surprising since the fuel cycle is mostly closed. The emissions of key pollutants correspondingly stem from the three other life cycle steps (construction, operation and disposal), except for pollutants such as Carbon-14 and Iodine-129 (consumption of electricity for operation).

Synthèse

Ce document est un livrable du projet NEEDS, et des projets EDF R&D associés : Inextenso P104S pour la période 2004-2006 ; NEEDS Prospective P10KH pour la période 2007-2008.

Contexte de NEEDS :

Le projet européen du 6ème PCRD NEEDS (New Energy Externalities Developments for Sustainability) s'étend sur 4 ans à partir du 1er septembre 2004.

Deux méthodes ont été retenues pour intégrer les préoccupations environnementales dans la prospective :

- une méthode d’optimisation économique : dans ce cadre, NEEDS vise à élaborer une modélisation de prospective énergétique prenant en compte les coûts externes,
- une méthode basée sur les indicateurs et des méthodes multicritères d’aide à la décision.

L’objectif final est d’orienter les politiques énergétiques de l’Union Européenne et des Etats Membres ainsi que les systèmes de régulation associés.

Contexte et objectifs de la roadmap technologique :

Ce document s’inscrit dans l’approche d’optimisation économique effectuée par NEEDS. Pour chaque filière électrogène, le raisonnement de NEEDS s’effectue sur la base suivante :

- une roadmap technologique de 2000 à 2050, avec plusieurs scénarios d’évolution (pessimiste, raisonnablement optimiste, très optimiste),
- une spécification des installations de référence pour les années 2000, 2025, 2050, sur les plans techniques, économiques et environnementaux. La définition de l’installation de référence à l’année 20nn est l’installation qui serait choisie pour une mise en service industrielle à l’année 20nn.
- Les données économiques issues des roadmaps sont destinées à alimenter le modèle TIMES, qui permet d’élaborer des scénarios par une méthode d’optimisation économique dans NEEDS.

En complément, les données d’inventaires de cycle de vie (LCI) sont fournies pour chaque technologie de référence.

Roadmap technologique de l’énergie nucléaire

Le document décrit les principes de base de la production d’électricité nucléaire ainsi que la gestion du cycle du combustible, fondamentale pour une approche d’évaluation environnementale.

Dans une perspective historique et prospective, les développements passés sont rappelés, et les développements futurs en cours sont exposés, en particulier le Forum International sur la Génération IV, le GIF.

Les raisonnements sur la place du nucléaire dans le mix énergétique mondial reposent sur une approche par scénarios, qui considèrent des facteurs tels que la compétitivité relative du nucléaire par rapport aux autres filières (paramètres tels que prix des combustibles fossiles, efforts de réduction des gaz à effet de serre), ainsi que le niveau et le prix des ressources en Uranium.

Les scénarios sont les suivants :

- scénario pessimiste : stagnation ou diminution du nucléaire mondial,
- scénario raisonnablement optimiste : croissance du nucléaire vers 1500 GWe nucléaires en 2050,

- scénario très optimiste : 2500 GWe nucléaires en 2050 (ce qui nous semble irréaliste).

Pour chaque horizon de temps, les inventaires de cycle de vie sont représentatifs de l'état de l'art des technologies disponibles dans le parc de production européen. C'est donc la « meilleure technologie disponible » qui a été retenue pour chaque année de référence.

Installations de références aux horizons 2000, 2025, 2050

Le système de référence pour l'année 2000 est un Réacteur à Eau Pressurisée tel que décrit dans les bases de données ACV[3] internationales « PWR[4] 1000 MW », associé à un enrichissement du combustible par diffusion gazeuse.

Le système de référence pour l'année 2025 est un EPR[5], associé à un enrichissement du combustible par ultracentrifugation.

Pour l'année 2050, il faut raisonner selon les scénarios :

- dans le cas du scénario pessimiste, on n'imagine pas de besoin de développer une quatrième génération de réacteurs, et le système de référence serait toujours un EPR ;
- dans les autres cas, des tensions peuvent se faire sentir sur la ressource en uranium, qui conduisent à l'émergence de réacteurs surgénérateurs de quatrième génération.

  Le réacteur qui est retenu est un Réacteur Rapide au Sodium. En effet, grâce au projet EFR[6], et au recueil de données environnementales sur la base de la connaissance de SuperPhénix, de nombreuses données économiques et environnementales sont disponibles, avec la maille de précision assez fine qui est demandée par NEEDS.

Les technologies de référence pour chaque combinaison scenario/an, correspondant aux besoins de NEEDS RS1a, sont listées dans la Table 11 de ce document.

Coûts des installations de référence

Les coûts de référence présentés dans ce document sont des coûts économiques actualisés, extraits de références de la littérature.

Le taux d'actualisation retenu pour le nucléaire dans NEEDS est 6 %, la monnaie de référence est l'€ 2000. On suppose qu'il n'y a pas de dérive des coûts au fil du temps.

Pour l'année 2000, sur la base des coûts de référence DGEMP 1997 portant sur le palier N4, on a un coût de production de 27 €/MWh (cf. Table 4).

Pour l'année 2025, sur la base des coûts de référence DGEMP 2003 portant sur l'EPR, on a un coût de production de 24,4 €/MWh (cf. Table 9).

Pour l'année 2050, les mêmes hypothèses que précédemment portant sur l'EPR, associées à un renchérissement de l'uranium, conduisent à un coût de production de 30,5 €/MWh dans le cas d'un EPR (cf. Table 10, première colonne).

A ce même horizon, un réacteur à neutrons rapides pré-Génération IV conduirait à un coût de production de 27,5 €/MWh (cf. Table 10, seconde colonne), moyennant les hypothèses suivantes : coût du cycle combustible 3,85 €/MWh (ibidem), surcoût d'investissement de 30 % par rapport à un EPR.

Avec des hypothèses optimistes sur les objectifs de Génération IV, qui consistent en l'annulation du surcoût d'investissement, on arrive même à un coût de production de 22,9 € /MWh (cf. Table 10, tiers colonne).

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[3] *Analyse de Cycle de Vie*

[4] *Pressurised Water Reactor*

[5] *European Pressurised Reactor*

[6] *European Fast Reactor*

Données d'inventaire de cycle de vie

La qualité et la représentativité des données utilisées pour la réalisation des inventaires de cycle de vie ont été les deux critères essentiels. Pour chaque horizon de temps, les données retenues sont considérées comme représentatives des réacteurs nucléaires de même type (opérationnels en Europe) en termes d'inventaires sur le cycle de vie.

Pour l'horizon 2000, les données sont extraites de la base de données suisse ecoinvent qui constitue à ce jour la base de données publique de référence. Les résultats d'inventaire du PWR mettent en évidence la prédominance de l'étape « combustible » en termes d'émissions des principaux polluants (CO_2, CH_4, NO_x, NMVOC, Radon-222 and SO_2) Cette étape comprend notamment les phases d'extraction et d'enrichissement de l'uranium.

Pour l'horizon 2025, le cycle nucléaire retenu comprend un réacteur de type EPR avec un enrichissement par centrifugation. Les données collectées correspondent au projet EPR de Flamanville (France) et sont complétées par défaut par des données issues de la base de données ecoinvent. A l'image du PWR, l'étape « combustible » est la principale contributrice aux émissions des principaux polluants cités précédemment.

Pour l'horizon 2050, l'analyse porte sur le réacteur EFR (European Fast Reactor), considéré comme représentatif des réacteurs rapides au sodium. Un travail spécifique de collecte de données relatives à l'EFR, réalisé avec des experts EDF impliqués dans le projet Superphénix, a permis de disposer de données pour la réalisation de l'inventaire. Par défaut, des données extraites de la base ecoinvent ont été utilisées. Contrairement aux deux cas précédents, l'étape « combustible » a une contribution marginale aux émissions des principaux polluants (CO_2, CH_4, NO_x, NMVOC, Radon-222 et SO_2) ce qui n'est pas surprenant dû au cycle quasi fermé pour le combustible. Ces émissions se répartissent entre les étapes de construction, de fonctionnement et de déconstruction de la centrale, à l'exception des émissions de Carbone-14 et Iode-129, provenant de la consommation d'électricité réseau lors de l'exploitation.

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LIST OF ABREVIATIONS

ABWR	Advanced Boiling Water Reactor
BWR	Boiling Water Reactor
CANDU	Canada Deuterium Uranium, Reactor
COD	Commercial Operation Date
DOE	Department of Energy (U.S.A.)
EDF	Electricité de France
EFR	European Fast Reactor
EPR	European Pressurized Reactor
FBR	Fast Breeder Reactor
FOAK	First Of A Kind
GIF	Generation IV International Forum
HTR	High Temperature Reactor
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
LCOGE	Levelised Cost of Generated Electricity
LWR	Light Water Reactor
MHTGR	Modular High Temperature Gas-Cooled Reactor
MOX	Mixed Oxide Fuel (U, Pu) O2
MSR	Molten Salt Reactor (GEN IV)
NEA	Nuclear Energy Agency
NEI	The Nuclear Energy Institute
NPP	Nuclear Power Plant
NRC	(US) Nuclear Regulatory Commission
PSI	Paul Scherrer Institut
PWR	Pressurized Water Reactor
SFR	Sodium-Cooled Fast Reactor (GEN IV)
SWU	Separating Work Unit
UCTE	Union for the Co-ordination of Transmission of Electricity (i.e. the association of transmission system operators in continental Europe).
UOX	Uranium Oxide fuel

1. Introduction

This document aims at describing the types of nuclear power plant (NPP) and associated systems that are studied in NEEDS RS 1a WP 14 for the reference years (2000, 2025, and 2050).

The first part is devoted to a description of current nuclear power plant types, with an insight on the historic developments that have lead to these systems.

The second part describes the possible technology development pathways. Nuclear energy has some advantages, especially regarding economics and greenhouse gases emissions, but also some limitations due to very diverse concerns ranging from uranium availability in the future, waste management and disposal options, safety regarding potential severe accidents, or proliferation resistance.

The international project "GIF" – “Generation IV International Forum" has selected systems which would enable to overcome one or several of these limitations. The research is on its way on six concepts which could represent the future of nuclear energy. A lot of work has been done on an international scale, which enables to describe quite precisely what the reactors could be like.

In this document, we describe the chosen reference systems for which Life Cycle Inventories (LCIs[7]) and (internal) costs are provided for the purpose of the NEEDS project. These systems have to be representative of plants that would be **chosen for new build** at the considered years (2000, 2025, and 2050). In fact, **in the whole report, the considered years refer to the starting date of Commercial Operation for the plant (COD).**

2025 is quite straightforward with evolutionary concepts, but 2050 can be the scene for very diverse options regarding nuclear systems, ranging from:

- no Generation IV at all – evolutionary systems chosen for new plants in 2050;
- emergence of the Generation IV reactors that are the most known today and that already feature a certain potential for industrial maturity around 2040;
- emergence of very different concepts of Generation IV reactors, through an accelerated R&D process enabling them to be industrially mature before 2050.

Nuclear experts are not unanimous on these future perspectives, and on the associated drivers. Therefore, this document attempts to reflect the diversity of the points of views, and to be pragmatic in the conclusions too.

The choice of the study systems for the NEEDS project will then be based on pragmatic considerations:

In fact, study systems should be known precisely enough in order to enable a life cycle inventory. Even if it differs from a complete LCA, the life cycle approach chosen in NEEDS requires some accurate data on industrial plant and cannot be applied to a concept for which no plant has been completely designed, unless this concept includes data on the plant (materials…) and utilities (water, heat…). Besides, some future concepts are currently being developed by private firms which do not take part in the NEEDS project and the data may not be available for the project.

[7] In NEEDS an LCA is conducted starting from the LCI part of LCA (ISO 14040). By following the impact pathway approach, also impacts are assessed which are finally valued in monetary terms. As the chosen impact indicators (such as Years of Life Lost or cases of chronic bronchitis in case of human health impacts) do not strictly comply with a category indicator (such as human toxicity in this case; cf. ISO 14042), it can be said that an ISO-conform LCA is not conducted within NEEDS. In any case, the work presented in this document constitutes only the first part of LCA, without going as far as analysing the impacts.

The authors want to stress the fact that the study systems described here have been designed to suit the purpose of the NEEDS project and do not reflect the opinions of the authors or their organizations regarding the future developments of nuclear energy.

2. Nuclear power plants today

Nuclear power worldwide represents 10 % of the total electric capacity, but 17 % of the generated electricity (Enerdata 2005). In Europe, about 30% of generated electricity comes from nuclear power.

2.1. Principles of nuclear energy generation

Nuclear energy generation is based on a controlled chain reaction – in fact, the fission of nuclear fuels (among which uranium) generates enormous quantities of heat that can then be used in a steam turbine power plant.

Nuclear reactors differ from one another through the choice of three fundamental components of the system:

- **Fuel:** it can be for instance uranium, plutonium, or thorium. Uranium can be more or less enriched according to the technological choices.
- **Moderator:** it is a material which has the property of slowing down the speed of neutrons[8] to keep the chain reaction going in thermal reactors. Usual moderators are water, heavy water, and graphite.
- **Coolant:** it is a fluid extracting the heat, it can be for instance water, pressurised gas, or liquid metals like sodium.

The combination of these three components enables reactors to control a chain reaction in order to generate energy.

A nuclear system relies on technological choices for the reactor and for the fuel cycle. The complete description of a nuclear energy generation system therefore requires to give details on the reactor technology on one side, and the fuel cycle on the other side. After use, the fuel can be either disposed of, or partially recycled. In this case, waste is vitrified and managed towards final disposal.

2.2. The development of nuclear power: from Generation I to current systems

2.2.1. History: Generation I

The first Generation was developed in the 1950s and 60s with early prototype reactors, like Shippingport in the USA (the first Pressurized Water Reactor), or Magnox in the UK (gas cooled reactor moderated by graphite and fed with natural uranium).

The figure below gives an overview of the generations of nuclear energy systems. This is only an indicative overview, as the classifications and time horizons for future systems may vary according to countries or experts.

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[8] *Neutrons can be used in the chain reactions according to two different principles:*

- *Thermal neutrons – their speed must be kept under a certain limit, or the reaction will extinguish itself. For this reason, the corresponding plants include a moderator.*
- *Fast neutrons – in this case the fuel composition is such as to use the neutrons as generated from fissions at high speed, where the reaction can perpetuate itself at a controlled pace without the necessity of a moderator. Such reactors are called "Fast reactors".*

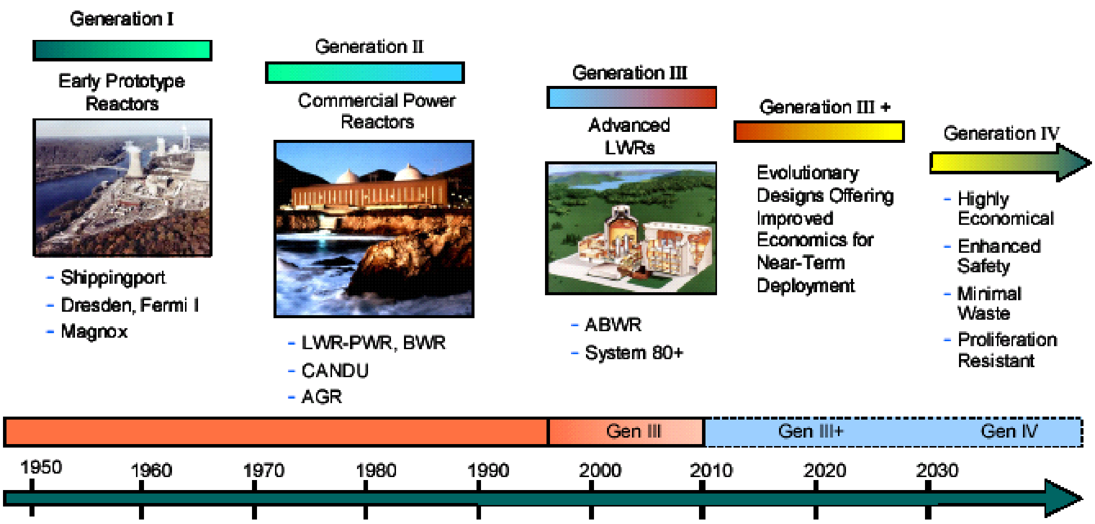

Figure 1: Nuclear generations according to the GIF (2002)

2.2.2. *The Present situation: Generation II*

The second Generation began in the 1970s in the large commercial power plants that are still operating today:

Reactor type	Main countries	Number	GWe	Fuel	Coolant	Moderator
Pressurised Water Reactor	US, France, Japan, Russia	285	255	enriched UO_2	water	water
Boiling Water Reactor	US, Japan, Sweden	90	79	enriched UO_2	water	water
Gas-cooled Reactor	UK	8	2	natural U enriched UO_2	CO_2	graphite
Pressurised Heavy Water Reactor	Canada	41	21	natural UO_2	heavy water	heavy water
Light Water Graphite Reactor (RBMK)	Russia	16	11	enriched UO_2	water	graphite
Fast Neutron Reactor (FBR)	Japan, France[9], Russia	3	1	PuO_2 and UO_2	liquid sodium	none
	TOTAL	443	369			

Table 1: Nuclear power plants in commercial operation at 31/12/2005.
GWe = capacity in thousands of megawatts. Source: IAEA 2006

Light Water Reactors (LWRs) contribute nowadays to roughly 90 % of the nuclear electrical power installed capacity, three quarters of LWRs being Pressurized Water Reactors (PWRs), which are by far the most common type of reactor operated today (60% of all reactors, two thirds of the installed nuclear power capacity in the world).

The fuel for these reactors is enriched UO_2.

[9] *Phenix Reactor is meant here, not SuperPhenix*

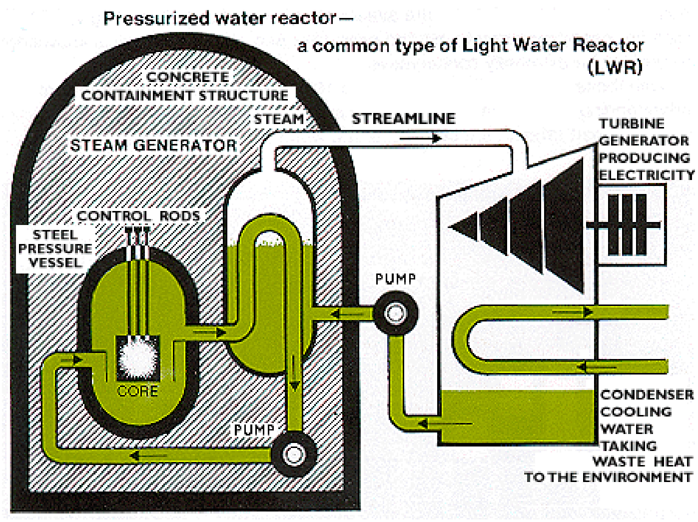

Figure 2: PWR reactors' general principle

The PWR design originated as a submarine power plant. It uses ordinary water as both coolant and moderator. The design is distinguishable from others by a primary cooling circuit, which flows through the core of the reactor under very high pressure (155 bars), and by a secondary circuit in which steam is generated to drive the turbine.

A PWR has fuel assemblies of 200-300 rods each, arranged vertically in the core, and a large reactor would have about 150-250 fuel assemblies with 80-100 tons of uranium.

Water in the reactor core reaches about 325°C, hence it must be kept under about 150 times atmospheric pressure to prevent it from boiling. Pressure is maintained by steam in a pressuriser. In the primary cooling circuit the water is also the moderator: therefore, if any of it turned to steam, the thermal neutrons would become too fast, and the fission reaction would slow down. This negative feedback effect is one of the safety features of this type of reactor. The secondary circuit is under lower pressure and the water here boils in the heat exchangers, which are thus steam generators. The steam drives the turbine to produce electricity, and is then condensed and returned to the heat exchangers in contact with the primary circuit.

The second most common type of reactors is the Boiling Water Reactor (BWR), whose design has many similarities with the PWR, except that there is only a single circuit in which the water is at lower pressure (about 75 times atmospheric pressure) so that it boils in the core at about 285°C:

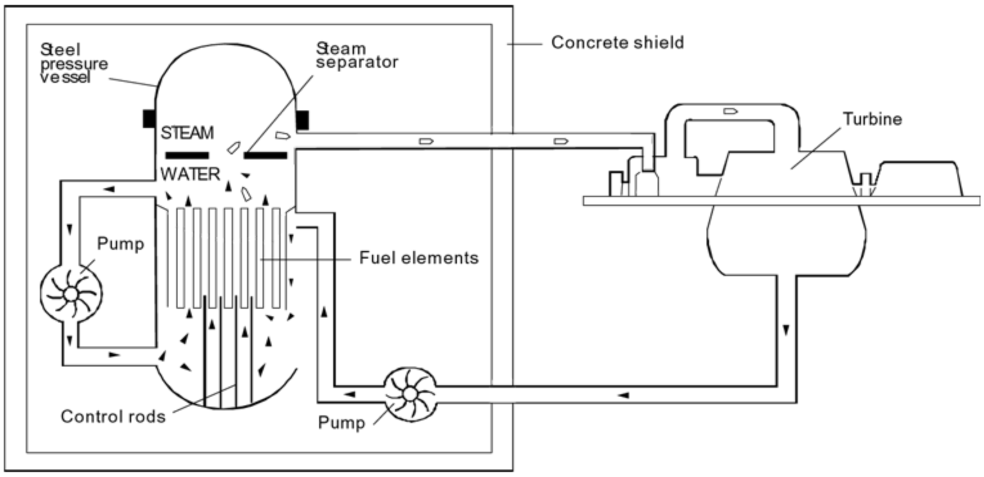

Figure 3: BWR reactors general principle

The reactor is designed to operate with 12-15 % of the water as steam in the upper part of the core. The steam passes through drier plates (steam separators) above the core and then directly to the turbines, which are thus part of the reactor circuit. Since the water around the core of a reactor is always contaminated with traces of radionuclides, it means that the turbine must be shielded and radiological protection provided during maintenance. The cost of this tends to balance the savings due to the simpler design. Most of the radioactivity in the water is very short-lived (mostly N-16 nitrogen isotopes, with a 7 second half-life – meaning that half of the radioactive N-16 isotopes have disappeared after 7 seconds of life, by decaying into oxygen-16), so the turbine hall can be entered soon after the reactor is shut down. A BWR fuel assembly comprises 90-100 fuel rods, and there are up to 750 assemblies in a reactor core, holding up to 140 tonnes of uranium.

Three other types of nuclear system have been commercially developed, but at a far lower level and in specific countries: the **Gas Cooled Reactor** in the UK, which uses carbon dioxide gas (CO2) as coolant, graphite as neutron moderator, and natural or enriched uranium as fuel; the **Pressurized Heavy Water Reactor**, mainly in Canada (CANDU reactors, CANDU meaning CANadian Deuterium Uranium, deuterium being the heavy isotope of hydrogen which is a component of the heavy water molecule), which uses heavy water as coolant and neutron moderator, and natural uranium as fuel; and the **Light Water Graphite Reactor**, mainly in Russia (RBMK type), which uses water as coolant, graphite as neutron moderator and enriched uranium as fuel.

To conclude with this overview, we must mention a few Fast Breeder Reactors prototypes built at commercial scale in Japan, Russia and France.

2.2.3. Generation III

The second Generation was followed in the 1990s by a number of evolutionary designs called Generation III systems that offer significant advances in safety and economics. Further advances are underway, resulting in several near-term deployable plants that are actively under development and are being considered for deployment in several countries around 2010.

On the whole, like Generation II systems, Generation III reactor designs are based on the improvement of already existing designs. It is thus not surprising that most Generation III reactors are advanced light water reactors, like AP 1000 (Advanced Pressurized – 1000 GWe) proposed by Westinghouse[10], ABWR (Advanced Boiling Water Reactor) and ESBWR (Economic Simplified Boiling Water Reactor) proposed by General Electric[11], or SWR 1000 (Simplified Water Reactor) proposed by AREVA. We can also quote VVER AES 2006 (1200 MWe - Atomenergoprojekt), APWR (1550 MWe - MHI), APR 1400 (1450 MWe - KOPEC) and in the CANDU technology, ACR 1000 (1200 MWe - AECL)[12].
The main evolutionary trends are in the continuity of Generation II:

- Improved safety, particularly by implementing passive safety features and simplification of the design,
- Better competitiveness thanks to:
    - lower generation costs, with enhanced fuel performances (higher burn up, longer operating cycle, recycling of plutonium),
    - longer reactor life span: it was initially 40 years for Generation II PWRs, but it could most likely be extended for existing reactors[13], and could directly be aimed at 60 years for Generation III systems.
- Reduction of highly radioactive waste and improvement of waste management.

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[10] *could also be quoted as Toshiba/Westinghouse*

[11] *could also be quoted as GE/Toshiba/Hitachi*

[12] *see the genealogy of CANDU reactors : http://www.eacl-aecl.ca/Assets/Publications/Posters/CANDU-Evolution.pdf*

[13] *In the USA, licences have already been granted for 60 years operation*

The European Pressurized Reactor (EPR) developed by Framatome-Siemens is a good representative of these Generation III reactors. The EPR uses moderately enriched (up to 5%) uranium oxide fuel or mixed oxide fuel (MOX). Its net electrical output is in the range of 1,600 MWe.

Advantages of the EPR include:

- Important gains in performance including availability over 90% and lower operating costs, translating into greater cost-competitiveness.
- Significant safety improvements: the probability of a core meltdown, already extremely low with the PWR, should be even lower with the EPR. But if such an event were nevertheless to occur, there should be no significant impact outside the power plant due to the extremely strong containment building surrounding the reactor.
- An answer to sustainable development concerns: by design, the EPR generates more electricity from a given quantity of fuel, thus conserving uranium resources (15 % decrease in the amount of uranium used) and generating less waste (15 % decrease). Among other factors, the conversion rate of thermal power into electricity rose from 34 % to 36-37 %.

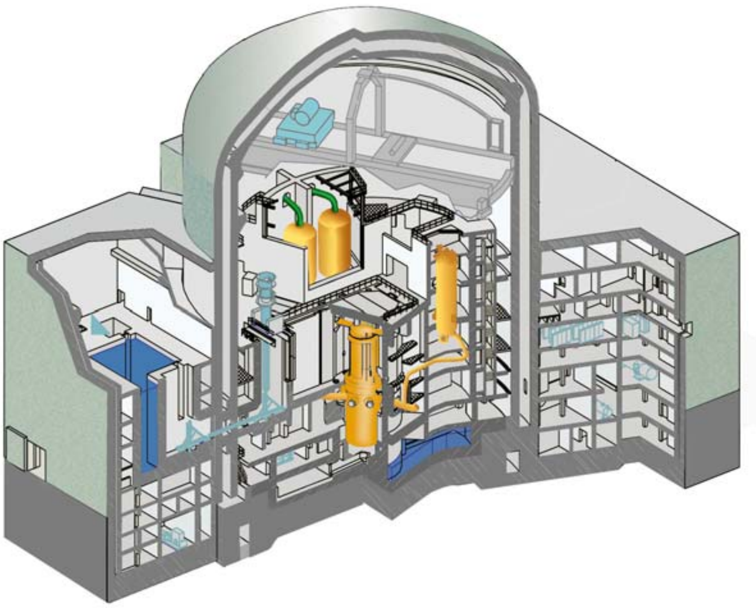

Figure 4: Schematic view of the European Pressurized Reactor (EPR)

2.3. Overview of nuclear cycle for current LWRs

The NEEDS project requires a life cycle inventory (LCI) for Nuclear Energy. Therefore, we describe the nuclear cycle as it will be the basis of our work.

During its preparation for use in a nuclear reactor, the uranium undergoes the steps of mining and milling, conversion, enrichment and fuel fabrication. These steps make up the front end of the nuclear fuel cycle. After the uranium has been used in a nuclear power plant, the spent fuel may undergo further steps such as interim storage, reprocessing, and recycling before final disposal as waste. All these steps are part of the back end fuel cycle. The following figure shows an overview of the entire fuel cycle:

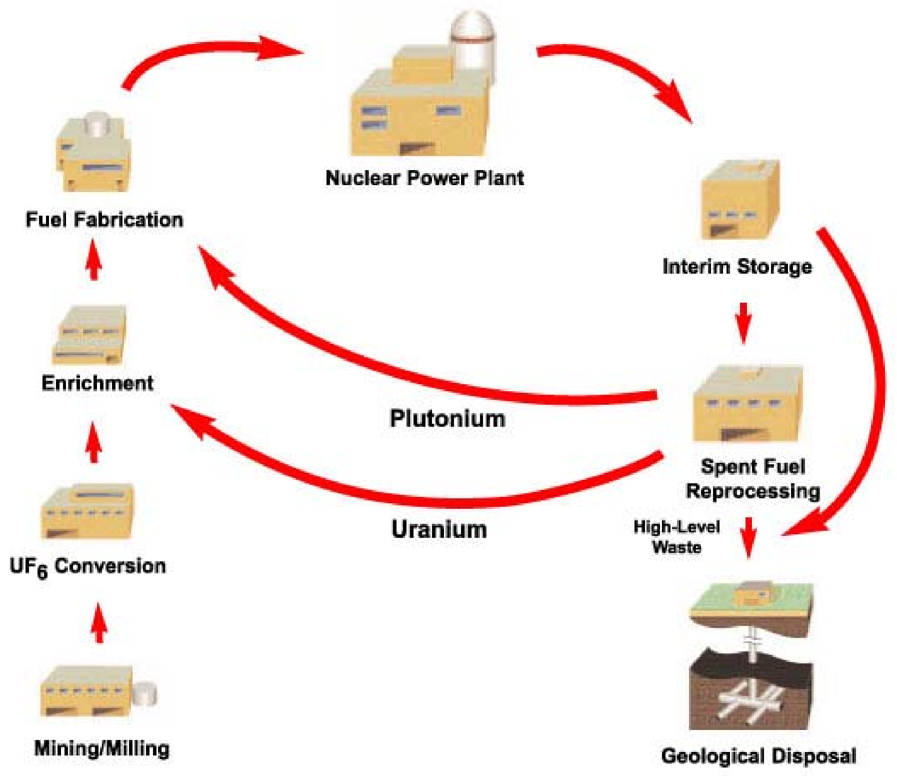

Figure 5: Nuclear Fuel Cycle – *source: www.uranium.info*

We will now briefly present each of these steps, from mining to final disposal of highly radioactive waste.

2.3.1. Mining and milling

Uranium ore is usually mined by either surface or underground mining techniques, depending on the depth of the deposit. The ore contains about 1 % uranium. The lumps of ore are crushed and milled to a fine powder in facilities close to the mine. Then this powder goes through a series of chemical processing steps, which result in a uranium oxide (U_3O_8) concentrated in the form of a yellow powder called “yellowcake”. About 200 tons of “yellowcake” are required to keep a large nuclear power plant (around 1000 electrical megawatts) generating electricity for one year.

2.3.2. Conversion and enrichment

Natural uranium cannot be used as such in most nuclear power reactors, because it contains 99.3 % of the uranium 238 (U-238) isotope, which is hardly fissionable: it is necessary to raise the proportion of the highly fissionable U-235 isotope from the natural level of 0.7 %. This enrichment process requires firstly converting uranium oxide U_3O_8 into uranium hexafluoride (UF_6). At 65°C (149ºF), the UF_6 is a gas, which is perfectly suited to enrichment by gaseous diffusion or ultra-centrifugation. The enrichment process separates gaseous uranium hexafluoride into two streams: one stream is enriched to the required level of U-235 (around 4 %, with a general trend to increase this enrichment up to 5 %), and then passes to the next stage of the fuel cycle. The other stream has a low U-235 content and is called 'tails'. It is mostly U-238 with only about 0.2 % of U-235.

The French uranium enrichment technology will soon be changed, with the replacement of gaseous diffusion by ultra-centrifugation which is 50 times less energy costly.

2.3.3. *Fuel production*

The enriched UF_6 is transported to a fuel fabrication plant where it is converted to uranium dioxide (UO_2) powder and sinterized into small pellets. These pellets are inserted into thin tubes, usually made of a zirconium alloy (zircalloy) or stainless steel, to form fuel rods. The rods are then sealed and assembled in clusters to form fuel assemblies for use in the core of the nuclear reactor. A 1000 MWe reactor requires some 25 tons of fresh fuel each year.

2.3.4. *Spent fuel storage*

Spent fuel assemblies taken from the reactor core are highly radioactive and give off a lot of heat. They are therefore stored in special pools, which are usually located at the reactor site, to allow both their heat and radioactivity to decrease. The water in the pools serves the dual purpose of acting as a barrier against radiation and dispersing the heat from the spent fuel.

The spent fuel can be stored safely in these pools for long periods. It can also be dry stored in engineered facilities, cooled by air. However, both kinds of storage are intended only as an interim step before the spent fuel is either reprocessed or sent to final disposal. The longer it is stored, the easier it is to handle, due to radioactive decay.

There are two alternatives for the spent fuel:

- Reprocessing to recover the usable portion of it;
- Long-term storage and final disposal without reprocessing.

2.3.5. *Spent fuel reprocessing*

The spent fuel still contains approximately 96 % of the initial mass of uranium oxide, of which the fissionable U-235 content has been reduced to less than 1 %. About 3 % of the spent fuel comprises waste products and the remaining 1 % is plutonium (Pu) produced while the fuel was in the reactor and not "burned" then.

Reprocessing separates the uranium and the plutonium from waste products (and from the fuel assembly cladding) by chopping up the fuel rods and dissolving them in acid to separate the various materials. Spent fuel reprocessing occurs at facilities mainly in Europe and Russia with capacity over 5000 tons per year and cumulative civil experience of 90,000 tons over almost 40 years:

Application	Plant	Capacity [t/y]
LWR fuel	France, La Hague UK, Sellafield (THORP) Russland, Ozersk (Mayak) Japan	1700 900 400 14 *3014*
Other nuclear fuels:	UK, Sellafield India	1500 275 *1775*
Total civil capacity:		4789

Table 2: World Commercial Reprocessing Capacity (tons per year),
Source: World Nuclear Association, Processing of Used Nuclear Fuel, 2005

The recovered uranium can be returned to the conversion plant for conversion to uranium hexafluoride and subsequent re-enrichment. The reactor-grade plutonium can be blended with depleted uranium to produce a mixed oxide (MOX) fuel, in a fuel fabrication plant. MOX fuel fabrication plants can be found in Belgium, France, UK, Russia and Japan, with more under construction. There have been 25 years of experience in this, and the first large-scale plant, Melox, started operation in France in 1995. Across Europe about 30 reactors are licensed to load 20-50 % of their cores with MOX fuel and Japan plans to have one third of its 54 reactors using MOX by 2010.

2.3.6. Waste vitrification and final disposal

After reprocessing, the remaining 3 % of high-level radioactive wastes (some 750 kg per year from a 1000 MWe reactor) can be stored in liquid form and subsequently solidified by calcinations to produce a dry powder, which is incorporated into borosilicate (Pyrex) glass to immobilise the waste. The glass is then poured into stainless steel canisters, each holding 400 kg of glass. A year's waste from a 1000 MWe reactor is contained in 5 tons of such glass, or about 12 canisters 1.3 metres high and 0.4 metres in diameter. These can be readily transported and stored, with appropriate shielding.

This is as far as the nuclear fuel cycle goes at present. The final disposal of vitrified high-level wastes, or the final disposal of spent fuel, which has not been reprocessed, has not taken place yet.

Final disposal of high-level waste is delayed to allow its radioactivity to decay. Forty years after removal from the reactor, less than one thousandth of its initial radioactivity remains, and it is much easier to handle. Hence spent fuel assemblies or canisters of vitrified waste are stored respectively under water in special pools, or in dry concrete structures or casks for at least this length of time.

The waste forms considered for disposal are vitrified high-level wastes sealed into stainless steel canisters, or spent fuel rods encapsulated in corrosion-resistant metals such as copper or stainless steel. The ultimate disposal of vitrified wastes, or of spent fuel assemblies without reprocessing, requires their isolation from the environment for long periods. The most widely accepted plans are for these to be buried in dry and stable rock structures deep underground. Many geological formations such as granite, clay, volcanic tuff, salt or shale will be suitable. Several countries are already investigating sites that would be technically and publicly acceptable[14] and most countries intend to introduce final disposal measures around 2020, when the remaining heat of the waste makes disposal possible.

2.4. Specification of present reference technologies

The specification in this paragraph is about a plant starting its commercial operation in reference year 2000.

This paragraph is based on the previous Technical Paper for NEEDS [Le Boulch 2006].

In 2000, the European nuclear fleet is mainly composed of Light Water Reactors. Among them, the PWR is the most common type of reactor since it represents about 80 % of the European installed reactors. Hence, **the PWR is assumed to be significantly representative for the current situation.** The analogy between PWRs and BWRs for LCI purposes is discussed in [Le Boulch 2006], as well as the choice of a representative size for the reactor, and some economic considerations.

In 2000, gaseous diffusion is providing more enrichment services to European plants than ultra-centrifugation (the Eurodif[15] plant, which uses gaseous diffusion, currently supplies nuclear plants in many countries, among which French reactors which make 50 % of the European nuclear fleet).

[14] *US: Yucca Mountain, France: Bure, Finland: Olkiluoto*

[15] *Eurodif means: European Gaseous Diffusion Uranium Enrichment Consortium.*

2.4.1. Technical data

The main characteristics of the present reference technology are summarized in the following table:

Parameter	Unit	Year 2000
	-	**Pressurized Water Reactor (PWR)**
Size	MW_e	1,000
Life time	Y	40
Enrichment process	-	Gaseous diffusion (Eurodif)
Main data sources	-	ecoinvent database R.Dones, 2003

Table 3: Overview on the reference nuclear power plant for the 2000 situation

The reason for choosing a 1000 MW reactor is that, although most recently installed European PWR units have higher capacity, the LCI data for the 1000 MW type were more accurate in Dones (2003). Anyway, this choice is conservative from the viewpoint of LCI results because the larger units would exhibit slightly lower LCI cumulative results for the better material utilization in the power plant and its higher thermal efficiency.

In this reference case, fuel enrichment is performed by gaseous diffusion, with a 3.8 % U235 enrichment. Enrichment is assumed to take place entirely at the Eurodif plant (France) which is supplied by nuclear power.[16] This enrichment rate is consistent with a discharge burn up of 45 000 MWd/t.

As France represents the largest nuclear country within EU25, some assumptions reflecting the French fuel cycle have been chosen: UOX spent fuel is reprocessed, fission products and minor actinides are sent to vitrification, and plutonium resulting from spent fuel is mono-recycled in MOX assemblies. Spent MOX fuel is kept in interim storage facilities.

2.4.2. Cost data[17]

Aside the technology in operation, the cost of the power generation depends on many parameters, such as:

- serial effect,
- discount rate,
- currency and exchange rate,
- economic life time[18],
- construction time and expense time schedule during construction, load factor,
- funds dedicated to fuel reprocessing, plant dismantling and site cleaning, waste treatment and disposal.

[16] *Although consideration of the centrifugal enrichment quota for the European nuclear park may introduce some differences in the cumulative results, these are not expected to be significant in comparison with cumulative results of other energy systems, notably fossils (cf. Dones et al. 2003).*

[17] *Reminder: this section is a literature review and should not be regarded as the judgment of the authors' organizations on the cost of nuclear energy.*

[18] *Economical lifetime is inferior or equal to technical lifetime. In the literature, different sources take different economical lifetimes into account for the same technical lifetime.*

Most of the levelised costs of generated electricity (LCOGE) for recent PWRs around year 2000 are between 20 and 40 $€_{2000}$/MWh [Chicago 2004], for a commercial operation date around 2010, LCOGE falls within the range of 31 to 46 $\$_{2003}$ (i.e. 25 to 38 $€_{2000}$/MWh) for a non FOAK unit.

In addition, the US nuclear generation (103 reactors in operation) has achieved noticeable progress during the last ten years; this increased the average availability factor to more than 90 % over the three years 2001-2003 [Stricker 2003].

The weight of the long-term expenses, such as NPP dismantling and waste disposal, in the generation cost depends mainly on the long term expenses management.

As an illustration, most of the studies estimate the NPP dismantling cost (including site cleaning) at around 15 % of the initial total investment. When actualised with a 6% discount rate, the dismantling cost appears to be only about 1% of the initial total investment (see Table 4 below)

Waste treatment and disposal of all types of radioactive waste are usually included in the fuel cost. In the same manner, when actualised, the waste disposal cost is less than 5% of the total actualised fuel cost [DGEMP] and highly dependent on the discount rate: This cost is paid at the end of the reactor operation, so the rules of economic calculation tend to make it low compared to the actualised benefits produced by the reactor operation.

The main technical and cost data of the nuclear power generation for C.O.D. reference year 2000 are shown in Table 4. The original source is [DGEMP 1997], for a reactor type PWR - N4 series, and for base load generation with a Commercial Operation Date (C.O.D.) 2005. In the following columns, data have been adapted for NEEDS usage to account for reference currency and for an economic lifetime of 40 years (DGEMP uses 30 years). In addition, the discount rate has been set to 6% in the last column of Table 4 as agreed within NEEDS RS1a.[19]

[19] Such a low discount rate is related to certain assumptions regarding the future. For instance, OECD/IEA 2006a states that a low discount rate case corresponds to a moderate risk investment environment, where construction, operating and price risks are shared between the plant purchaser, the plant vendor, outside financiers and electricity users, through arrangements such as long-term power-purchase agreements.

Table 4: Main technical and cost data for the mean nuclear power generation (General assumptions: C.O.D. Year 2000, Base generation)

Parameters	**Unit**	**Original Reference Data [DGEMP 1997]**	**Idem with 40 years lifetime**	**Data translated for NEEDS usage**
Currency (Cur.) reference year[20]		FF 1997	FF 1997	€ 2000
Discount rate		5	5	6
Technology		PWR, N4 series in France (2nd train, 10 units)	PWR, N4 series in France (2nd train, 10 units)	PWR, N4 series in France (2nd train, 10 units)
Size	MW_e	1450	1450	1450[21]
Economic life time	Years	30	40	40
Construction time	Years	5.75	5.75	5.75
Availability	%	84	84	84
1→ Overnight investment cost[22]	Cur./kW_e	8619[23]	*Idem*	1356
2→ interest cost during construction	Cur./kW_e	1335	*Idem*	254.5
3→ dismantling cost[24]	Cur./kW_e	212	~130	13.1
4→ Total investment cost 4 = 1+2+3	Cur./kW_e	10166	10089	1624
5→ Total Investment cost	**Cur./MWh_e**	**87.2**	**77.4**	**14.1**
Fixed O&M cost	Cur./kW_e/y	1.1[25] x 190	1.1 x 190	32.8
Variable O&M cost	Cur./MWh_e	1.1[25] x 5.0	1.1 x 5.0	0.86
6→ Total O&M cost	**Cur./MWh_e**	**33.7**	**33.7**	**5.29**
7→ R&D cost	**Cur./MWh_e**	**3.6**	**3.6**	**0.56**
8→ Fuel cost included up and downstream	**Cur./MWh_e**	**44.9**[26]	**44.9**	**7.04**
Levelised cost of generated electricity = 5+6+7+8	**Cur./MWh_e**	**169**	**159.6**	**27.0**

[20] *Conversion table given in appendix.*

[21] *The economic data refer to a 1450 MW reactor. The environmental data are given for a 1000 MW reactor.*

[22] *Including construction and possible engineering cost, pre-operation cost, risks on planning.*

[23] *In [DGEMP 1997] decomposition is the following: construction cost + engineering cost + pre-operation cost + risks on planning.*

[24] *Dismantling cost is estimated as 15% of the total investment cost (1+2)*

[25] *10% overheads coefficient including taxes*

[26] *figure given on a basis of 20 USD/lb for U_3O_8 price (i.e. 52 USD/kg Unat) and 6.50FF= 1 USD*

3. Nuclear technology development pathways

3.1. Nuclear development hot spots

On the one hand, nuclear energy could be an efficient technology for baseload generation in the future, with some strong points on the economic side; on the other hand, it would have to overcome some of its limitations. These strong and weak points are described in the table and in the list below:

Weak points / potential barriers	Strong points / factors favouring diffusion
Safety: risk of severe accident, although very low	Competitiveness: low electricity generation costs
Waste management	Reliable energy resource: uranium supply in the short-medium term, and possibility of breeders then
Potential risk of proliferation	Close-to-zero CO_2 emissions
Financial risks: high capital needs	Dispatch ability: reliable energy source
Controversial social acceptability[27] -	Low sensitivity to fuel costs

Table 5: Nuclear development hot spots

Nuclear energy has some strong points that led to its diffusion until now:

- Beyond the low generation cost, the reliability of such a kind of energy for baseload generation makes it a good option for electricity supply. The fuel costs weigh only a few percents in the generation costs. This enables one to plan the costs much better than with fossil fuels in the current context.
- Among other energy sources with close-to-zero CO_2 emissions, nuclear energy features an ability to be dispatched, which is very significant for the grid operators.
- Uranium is in the short-medium term a reliable resource, and in the long term, technological progress should allow nuclear to use uranium in such a way that resources would be reliable for many decades more.

In order to overcome the difficulties and foster the development of nuclear power, nuclear energy will have to satisfy the following major conditions:

- Maintaining a high level of **safety**, in accordance with international rules and state of art, with enhanced safety culture at all management levels and safety reassessment process, and enhanced radiological protection, in accordance with the ALARA[28] principle and new international standards;
- Maintaining the overall **competitiveness** of nuclear energy in the long term, a necessary condition for its development and public acceptance;
- Pursuing the development of credible, technically and economically efficient solutions for a good management of the high level **waste** issue and for mastering the whole nuclear fuel cycle consistency, and meeting the long term institutional and financial responsibilities for spent fuel treatment, back end, and nuclear facilities dismantling;
- Preserving future options for **energy resources** and extending the nuclear fuel supply by recycling used fuel and by converting U-238 to new fuel in the future;

[27] *In some countries, the controversial social acceptability could be enhanced by a more open debate on technical choices with the basis of participative democracy (citizen juries). Nevertheless, it is no guarantee to obtain a consensus on nuclear.*

[28] *ALARA: As Low As Reasonably Achievable*

- Providing continued effective **proliferation resistance** of nuclear energy systems, through intrinsic barriers and extrinsic safeguards, and physical protection against terrorism;
- Reducing the **financial risks** associated with the building and operating of a nuclear power plant.
- Another key point for the development of nuclear energy is the development of participative procedures, along with the sharing of knowledge and issues concerning the long term energy future, which should result in a greater transparency and legitimacy of decisions. This last point is country specific.

To conclude this part, we can state that some hot spots can be regarded as weak or strong according to the energy system of reference in which a facility is built, for instance:

- Centralized facilities with high energy density can present the advantage of not depending on the grid and on the energy planning policy;
- The structure of generation costs, with a high capital part and low variable part, can be an advantage or a drawback, depending on the economic context (discount rate).

3.2. Main drivers influencing future technology development

The main drivers influencing future technology development are linked to the hot spots described previously. Two questions have to be distinguished:

- how much nuclear will be built worldwide?
- which kind of NPPs will be built after 2030?

The answers to the first question depend on several parameters that will be dealt with later below.

The answers to the second question are more complicated: they are a result of

- current technology developments,
- answers to the first question and concerns of scarcity regarding primary (or natural) uranium,
- other drivers, corresponding to other hot spots, that could be more important to decision-makers than the one regarding competitiveness and uranium availability. Indeed, the different Generation IV reactors have different features regarding the different hot spots. We could imagine that the society in the future considers that the solving of one or several issues could be the trigger for the development of specific nuclear systems.

The relative judgment towards the different drivers can vary very widely according to the preferences of the decision-makers in the future. We have no access to them.

In conclusion, we stick to an approach where the main drivers are: fossil fuels scarcity, policy focus on climate change, competitiveness, foreseeable technical development state, and natural uranium scarcity.

3.2.1. How much nuclear will be built worldwide? The place of nuclear energy in the energy mix

The development of nuclear energy on a world scale can be yielded by several drivers, among which the most significant are related to its role in an energy mix.

The question consists in meeting the growing energy demand, using the following possibilities: energy efficiency, renewable energies sources, fossil energy sources (with or without carbon capture and storage), and nuclear electricity generation.

Therefore, we suggest that the main drivers leading to nuclear energy development are:

- growing electricity demand on a world scale (especially in developing countries),
- high prices of fossil fuels and especially of gas for electricity generation,
- endorsement of policies for CO_2 mitigation, making fossil electricity generation very expensive.

Under these circumstances, nuclear power generation, which emits almost no CO_2, would be very competitive and could develop fast.

It is noteworthy to remind that the several hot spots described above can also yield a development or slowdown of nuclear energy.

Social acceptability could play a different role in different parts of the world as well as in different European countries – and therefore, regional specificity should be taken into account when dealing with this topic.

3.2.2. Focus of R&D efforts regarding nuclear power plants indicate the foreseeable future plants

Current R&D programs are dealing with the issues raised previously and aim at following objectives:

- Further improve competitiveness (fuel management, reliability, availability, lifetime extension,...);
- Further improve safety and radioprotection,
- Improve emission control,
- Further develop and implement long term solutions for reducing the generation of wastes and their management and disposal,
- Extend the lifetime of natural uranium reserves by improving the use of uranium required to generate electricity,
- Increase proliferation resistance, through intrinsic barriers, extrinsic safeguards and physical protection.

R&D is aimed at all points in the nuclear cycle, from mining to extraction to back-end decommissioning. The reactors of Generation III have been developed in the 1990s with a number of evolutionary designs which offer significant advances in safety and economics and a number have been built or are being built. Advances to this generation are underway, resulting in near-term deployable plants which are actively under development. These plant types are likely to be the chosen design for new nuclear build between now and the middle of the century. Beyond then, the prospect for innovative nuclear systems has stimulated worldwide interest in a fourth generation: it is the objective of the Generation IV International Forum (GIF).

The basic foundation of the GIF is the recognition, by its members, of the advantages of nuclear energy to satisfy increasing needs of energy in the world in a context of sustainable development. This is put in concrete form by the common will to create an international framework to define and develop 4th generation nuclear systems (reactors and fuel cycle) until their industrial maturity around 2040. The GIF regroups eleven countries, among which the USA, France, Japan, the UK, Canada, South Korea, as well as the countries which signed the Euratom treaty, and China and Russia since the end of November 2006.

A hundred of international experts contributed to the first phase of the GIF (2000 – 2002). This phase was concluded by the issue of a technical report, the Technology Roadmap for Generation IV Nuclear Energy Systems, which identifies the most promising technologies for the next decades [GIF 2002]. Six nuclear systems have been selected, to allow significant advances in economical competitiveness, safety, long life radioactive waste reduction, uranium resources preservation and proliferation resistance and physical protection. These six systems are the following:

- GFR (Gas-Cooled Fast Reactor System): fast spectrum gas cooled reactor – closed fuel cycle;
- SFR (Sodium-Cooled Fast Reactor System): fast spectrum sodium cooled reactor – closed fuel cycle;
- LFR (Lead-Cooled Fast Reactor System): fast spectrum lead or lead-bismuth cooled reactor – closed fuel cycle;
- VHTR (Very High Temperature Reactor System): thermal spectrum, initially envisaged in open fuel cycle. The VHTR is a graphite moderated, helium cooled reactor, with an helium exit temperature expected to reach a level which would allow hydrogen production with a high efficiency (around 1,000°C) ;
- SCWR (Supercritical Water-Cooled Reactor System): thermal or fast spectrum, supercritical water cooled reactor – closed fuel cycle;
- MSR (Molten Salt Reactor System): thermal spectrum, molten salt fuel (Thorium) reactor – closed fuel cycle.

These systems are aimed at electricity generation but some have the potential to co-generate hydrogen from water or to produce high temperature heat for industrial processes. Out of these six systems, five use a closed fuel cycle and four use fast neutrons *(fast neutrons are able to regenerate nuclear fuel – cf. footnote 8)* – which shows the importance given to the objectives of fuel resources preservation and waste minimization.

3.2.3. Nuclear development under a constraint of limited amount of uranium resources

We consider now that fuel supply could be a concern in the 21st century for different fuels – for fossil fuels (oil and gas) of course, making nuclear more attractive, but also for natural or primary uranium, under some specific conditions.

The status of primary uranium resources, taken from the ‘Red book’ [OECD 2005], is indicated in Table 6, as a function of the cost of recovery. In the 2005 edition, the Identified Resources are estimated at a level of 4.7 MtonsU, the Conventional Resources at 14.8 MtonsU and the amount of Unconventional Resources associated with uranium in phosphates at about 22 MtonsU. These estimates display substantial uncertainties, be it for scarce prospecting for the last 20 years.

Table 6: Uranium resources (million tons U).

	Conventional				Phosphates
Cost of recovery ($/kgU)	Identified		Prognosticated	Speculative	
	RAR	Inferred			
< 40	1.947	0.799	1.700	4.557	22
40 - 80	0.696	0.362			
80 - 130	0.654	0.285	0.819		
> 130	–	–	?	2.979	
Total	4.743		10.055		

For the sake of simplification, two different levels are considered:

1. A lower level of 14.8 Mtons U, corresponding to *Conventional Resources* (given by the sum of Identified Resources – Reasonably Assured Resources (RAR) plus Inferred Resources – and of Prognosticated and Speculative Resources);

2. A higher level of 37 Mtons U, obtained by the addition of the uranium amount in Phosphates to the Conventional Resources.

In the case of an important nuclear development under the pressure of the drivers explained above, uranium resources would become less accessible and more costly.

A new generation of reactors with radically reduced uranium consumption could become necessary in the second part of the century (2050 – 2100). The date of emergence of these reactors could be determined by the actual nuclear demand and uranium resources. The scenarios described thereafter discuss this date of emergence.

3.2.4. Summary of the drivers for the emergence of Generation IV nuclear systems – with a priority set on uranium resources, waste, and industrial technology development

With such priorities set on Uranium resources, the Generation IV reactors would be breeders[29]. The envisaged drivers for nuclear fleets based on breeder reactors are the following:

- **Concern about the scarcity of uranium resources:** Uranium scarcity could occur due to a massive development of nuclear generation, itself due to too high fossil fuel prices for electricity generation and climate change mitigation policies.
  To summarize the uncertainties in this field, this depends on the real amount of uranium resources available at a reasonable price and on the growth of nuclear electricity demand – the latter depending on the growth of electricity demand and on the relative costs of nuclear and fossil electricity generation, both in terms of economy and of their contribution to climate change mitigation.
- **Concern about high-level waste:** There is another incentive to develop the FBR technology. Nuclear sustainability requires a good use of natural resources, but also strives to minimize the production of long life highly radioactive waste. In fact, the open cycle leads to a relatively rapid exhaustion of the uranium resource, as well as to the accumulation of highly radioactive waste in the form of spent nuclear fuel. Partial recycling of plutonium, with MOX fuel loading into LWRs as it is practised today in some countries, enables a significant reduction of this waste, but it remains limited if compared to FBRs, in which the plutonium (which is the bulk of long life radioactive waste) is entirely recycled (closed cycle strategy). Generation IV Fast Breeder Reactors could therefore be a response to the concern about high level waste produced by nuclear power plants.
- **Industrial constraints:** The time horizon of the availability of Generation IV systems on an industrial scale is a consequence of these drivers but also of the time span needed for research, development and industrialization. According to the experts, it seems quite unrealistic that Generation IV Fast Breeder Reactors with real technological breakthroughs could occur before 2040 at the earliest, due to technical and industrial constraints.

Of course, the share of Generation IV reactors in 2050 depends on the starting date of their deployment, which should not happen before 2040 according to our assumptions.

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[29] *A breeder reactor is a nuclear reactor that is specifically designed to create more fissile material than it consumes – therefore, it breeds fuel.*

3.3. Scope of study regarding scenarios and specifications for NEEDS project

The context of the study is following:

Study systems for NEEDS should be state of the art or “best available technologies” at the chosen years. That is to say, considering the possible development pathway of nuclear fleets described in this report, the systems chosen should be the newest ones (emerging and marginal in the energy mix) rather than the ones accounting for the largest share of the installed capacity.

The task for this paper consists in defining three scenarios that are to be called "pessimistic / realistic / very optimistic", according to the general instructions for RS 1a.

We will define these scenarios as follows:

- pessimistic → stagnation or decrease of nuclear energy worldwide;
- optimistic → increase of nuclear energy towards 1500 GW installed capacity in 2050;
- very optimistic → towards 2500 GW in 2050, which seems unrealistic to us.

3.4. Scenarios: the potential role of nuclear in a future energy supply system

In this chapter, several market development scenarios for NPPs will be proposed. They are consistent with the drivers exposed previously.

The aim of this description is to set the technology choices for the NEEDS LCA inventory. Having stated that the assumptions regarding nuclear energy capacity and type can vary widely, one can find some stability when looking at the industrial constraints of technology developments, as exposed below.

3.4.1. Constant over several scenarios: evolutionary reactors remain the most operated technology until 2050

Thanks to the long lifespan of nuclear plants (for Generation III) and to the work of the Generation IV International Forum, we have quite a good overview of future nuclear systems in comparison to other electricity generating facilities.

One special feature of nuclear power is the long time of technology development. When R&D on a NPP type is ended, the minimum required time for planning and construction of the prototype reactor is about 12 years, making it to 20 years for the First Of A Kind (FOAK) Reactor. For instance, if a NPP concept which is currently under discussion still needs about 10 years of R&D, it means that the FOAK will deliver its first MWh to the grid in 2035 at the earliest. Even if the building of new plants would proceed as fast as the industrial constraints allow it, we can consider that the part of such an innovative concept in the generation fleet could not be very high in 2050.

Therefore, regardless of the energetic scenario, the dominant technology in the period 2007-2050 will certainly be the evolutionary Generation III reactors, which are represented by the EPR in this report.

3.4.2. Scenario overview

We consider two main types of scenarios:

- Pessimistic scenarios: stagnation or decrease of nuclear production.
- Optimistic scenarios: strong increase of nuclear production on a global scale.

In both cases, evolutionary reactors like the EPR are requested in order to satisfy the demand (low or high) with the best available technology.

- In the pessimistic scenarios, there is not a high enough concern about uranium scarcity to stimulate the emergence of radically new technologies.
- In the optimistic scenarios, the need for reactors using less uranium (Generation IV Breeder Reactors with uranium consumption divided by 100 compared to Generation III, Cf. below) will come in 2040, so that **in 2050 the dominant technology will still be the evolutionary Gen III (for example EPR), and the first Generation IV reactors will be coupled to the electric grid**.

3.4.3. Pessimistic scenarios: stagnation or decrease of nuclear power

The reason for such a scenario could be a lack of acceptation by the public or a radical breakthrough of another electricity generation technology. In this case, there would be no massive nuclear energy development and the uranium scarcity concern would not be a driver for the emergence of radically new technologies.

We can imagine that in this case, there will not be any will to develop new nuclear concepts, and there will only be a smooth optimisation of the Generation III reactors. The waste minimization possibilities featured by some Generation IV reactors would not be a sufficient driver to displace the Generation III / EPR for new plants.

The reference technology in these cases is the EPR**.**

3.4.4. A "realistically optimistic scenario" – 1500 GWe in 2050

The scenarios depend on assumptions about the growth of electricity demand and about the nuclear share in the energy mix resulting of the preceding constraints. In this part we consider a "*realistically optimistic scenario*" based on an IIASA-WEC study [IIASA 2001] on Global Energy Scenarios to 2050 and beyond. We chose the WEC Scenario B, which represents a middle course, with a primary energy demand limited to 19.8 Gtoe in 2050.

Massara *et al.* (2006) calculated several scenarios among which one can be used as a "*realistically optimistic scenario*" for the NEEDS project. This scenario features a nuclear primary energy supply in 2050 as high as 2.5 Gtoe, corresponding to an installed nuclear capacity of 1500 GWe[30] (growth rate of 3.2 %/yr. between 2005 and 2050) [Massara 2006]. This translates into 0.97 Gtoe of final energy, i.e. electricity. The growth rate decreases to 1.4 %/yr. between 2050 and 2100, leading to a two-fold increased production in 2100 (5 Gtoe of primary nuclear energy, for an installed power of 3000 GWe). For this "*realistically optimistic scenario*", all the accessible uranium resources (15 Mt of conventional resources + 22 Mt of phosphates, that is 37 Mt) are engaged[31] in 2095, and it will be too late to deploy Fast Breeder Reactors. Therefore, a careful strategy would be to have a breeder technology available in 2040 – 2050.

The conclusion is that for this *realistically optimistic scenario*, the dominant technology in 2050 will be Generation III reactors (like the EPR), with the appearance of the first units of Generation IV reactors (at least the first demonstrators). These Generation IV units could be of different types, among which sodium cooled Fast Breeder Reactors should be ready for commercial deployment around 2040-2050.

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[30] Massara [2006] assumes a 86 % availability after 2020 and the following equivalence: 1 Gtoe = 4500 TWh_e. The electrical efficiency of the 2000 reference technology (i.e. the PWR N4 with an installed capacity of 1450 MWe) amounts to 0.34 [DGEMP 2004] while the target efficiency values are 0.37 for the EPR [EDF 2005] and 0.4 for the FBR [MIT 2003]).

[31] Uranium resources "engaged" in year 20nn are defined as the uranium resources that are necessary to run the reactors existing in year 20nn until their planned shutdown.

For comparison purposes, the MIT study [MIT 2003] features the same evolution of the reactor fleet until 1500 GWe in 2050, but it predicts the fleet will remain stable at 1500 GWe for 50 additional years. In this case, all uranium resources would be engaged in the first part of the 22nd century, entailing uranium scarcity only then.

3.4.5. The “very optimistic scenarios” – 2500 GWe (or more) in 2050

Scenarios based on the WEC Scenario A with large growth could lead to a higher demand for nuclear production. In [Bauquis 2001], dealing with the short term (2020) and medium term (2050) energy mix, the author[32] presents a scenario in which the emphasis is not on the uncertainties about energy demand, but on the potential limitations on the supply of fossil fuels and mainly of oil and gas. It results in a large increase of nuclear primary energy supply in 2050: 4 Gtoe which constitutes 22 % of the primary energy (18 Gtoe). This translates into 1.55 Gtoe of final energy, i.e. electricity. This scenario has been modelled up to 2050, when the installed nuclear capacity is 2400 GWe[30], and then extended up to 2100 with a low growth rate of about 1.2 %/yr. between 2050 and 2100. The installed capacity in 2100 equals 4300 GWe (7.2 Gtoe of primary nuclear energy).

In Massara *et al.*, this scenario has been modelled. It shows that all the accessible uranium resources (15 Mt of conventional resources + 22 Mt of phosphates) are engaged in 2080. To comply with such a constraining scenario, Generation IV reactors should be ready for industrial deployment in 2030, which is unrealistic from an industrial point of view, considering the time of development of a completely different nuclear reactor type and associated fuel cycle.

In this scenario with early deployment of Fast Breeder Reactors, the world nuclear fleet in 2050 could be composed of 50 % of Generation III reactors like the EPR and 50 % of FBRs, but such a scenario seems very improbable.

3.4.6. Other concerns, other scenarios

Of course, we can imagine completely different scenarios, featuring reactors responding to other concerns than uranium scarcity – for instance reactors enabling the joint production of high temperature industrial heat and electricity, known as VHTRs. Such reactors are envisaged for the production of hydrogen in some countries. Building scenarios featuring a deployment of VHTRs implies to have data on the part that these reactors could play in the energy mix, as well as on the industrial characteristics of these plants. There remain some uncertainties regarding the feasibility of such plants, mainly because such reactors present very hard technological challenges. The feasibility at industrial sites is also problematic: would heat generation and demand match, would public acceptability be better or worse for sites featuring both an industrial plant and a nuclear plant at the same time?

As it was too complicated for the purpose of this study, which is anyway embedded in a LCA modelling of future electricity options only, we chose not to develop such scenarios – but one must bear in mind that they are possible.

3.5. Technology development perspectives

3.5.1. High Temperature Reactors (Generation III+)

High Temperature Reactors (HTRs) use helium as coolant, graphite as moderator, and uranium oxide inserted in a coated particle graphite matrix as fuel (known as TRISO particle). The main advantages

[32] *Special Advisor to the Chairman of the Petroleum Company Total.*

of HTRs are their high efficiency due to high helium exit temperature (850°C), enhanced by the possibility of Brayton power cycle for electricity production (still to be demonstrated at an industrial scale), and interesting passive safety features (but with the constraint of keeping the reactor power below 600 MW_{th}).

These systems could be deployed in a relatively near future, but their feasibility on an industrial scale is not yet in place, and their performances in terms of fuel cycle are comparable to Generation III systems.

Two kinds of design are more particularly studied: the Modular High Temperature Gas Cooled Reactor (MHTGR), with a prismatic fuel, and the Pebble Bed Modular Reactor (PBMR) by Eskom. The fact that HTRs are classified among Generation III+ rather than Generation IV is sometimes disputed among experts[33]. In this report, we chose a classification in Generation III+; although it can be discussed, it is not the main focus of the report which deals with reference systems for a LCI study.

3.5.2. Nuclear systems selected by the Generation IV International Forum (GIF)

As stated before, the objectives and challenges for nuclear systems of the 4th Generation have been discussed in depth in the framework of the Generation IV International Forum (GIF), which was initiated by the US DOE in 2000 and issued its final report on Technology Roadmap for Generation IV Nuclear Energy System in December 2002 [GIF 2002]. According to this report, the main objective for Generation IV systems is to ensure nuclear energy's sustainable development.

The Generation IV International Forum has set several criteria to define "sustainable development".

One of these criteria implies the extension of the nuclear fuel supply into future centuries, and thus a good use of existing resources. The corresponding Generation IV reactors will be able to regenerate their own fuel: these reactors aim at consuming fifty to hundreds times less uranium than Generation III reactors. They could become necessary in order to answer concerns about the scarcity of uranium and its resulting price, or in order to minimize the amount of highly radioactive waste generated thanks to a closed cycle.

The Generation IV International Forum selected the six most promising nuclear systems on which R&D efforts should focus; four of them are Fast Breeder Reactors or FBRs, distinct by the coolant: sodium, lead, helium and super-critical water. Their deployment would entail strong consequences on the entire fuel cycle, requiring the development of an important fuel reprocessing capacity, but limiting and eventually ruling out the front end of the cycle (mining, conversion, uranium enrichment).

Another key requirement assigned to Generation IV nuclear systems is competitiveness. This goal can be met by traditional ways like simplifying and optimising nuclear plants design, improving fuel cycle efficiency, etc… already under progress with Generation III (see § 2.3). Competitiveness can also be enhanced by developing new applications of nuclear energy: hydrogen production, sea water desalination, district heating, process heat and other industrial applications of high temperature, … Among all the new applications that are considered, hydrogen production is the focus of particular attention, and one of the six Generation IV systems is specifically dedicated to this objective: the Very High Temperature Reactor (VHTR).

Generation IV reactors will also have to comply with other traditional criteria about safety, reliability, or proliferation resistance. But the most challenging objectives according to the GIF, clearly and strongly expressed by the Generation IV selection, are on the one hand to develop systems to ensure nuclear energy sustainability, and on the other hand to develop Very High Temperature Reactors for hydrogen production. These goals involve a considerable R&D effort to achieve the necessary breakthroughs.

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[33] *It is a question of temperature : VHTR (Very High Temperature Reactor) is a Generation IV reactor*

3.5.3. Generation IV with longer time horizon – Thorium Reactors

The development of the thorium cycle is envisaged, with a later date for feasibility. Thorium (Th-232), like U-238, is not fissile by itself, but can be transmuted into a highly fissile uranium isotope: U-233, in the same way that U-238 is transmuted into plutonium (Pu-239). Thorium is theoretically 3 times more abundant than uranium, and could thus bring a major contribution to nuclear energy sustainability, provided that breeder reactors are developed with a Th-232 / U-233 cycle.

However, the thorium cycle has not been singled out as a primary field of interest in the Generation IV International Forum, which has given priority to the uranium-plutonium cycle. There are several reasons for that:

- The uranium-plutonium (U-Pu) cycle is far more advanced than the thorium cycle, which features significant difficulties (high gamma activity due to presence of U-232);
- Known thorium resources are currently limited due to the lack of prospecting, and they are concentrated in a few countries;
- Designing a breeder reactor in order to close the thorium cycle is *a priori* more difficult and challenging than in the case of the U-Pu cycle, but interesting because U-233 breeding is possible in the thermal neutron spectrum.

The GIF consensus was that the development of the thorium cycle should arise later. Only India, which owns a huge resource of thorium on its territory (600,000 tons) but very little uranium, has engaged in an active research program on the thorium cycle, and plans to launch heavy water reactors with thorium as fuel on a large scale.

3.6. Indications on costs development

3.6.1. Preliminary discussion about fuel costs – sensitivity analysis on uranium price

The fuel cycle cost is divided into: uranium cost, conversion cost, enrichment cost, fuel production cost, back end cost (cost of the fuel reprocessing and waste disposal).

Table 7 below firstly shows the evolution of fuel cost for a Generation III reactor between 2025 and 2050 with the assumption of a relative stability on uranium price from the beginning of this work (year 2005) until 2025 and then a strong raise of uranium price from 62 €/kg Unat in 2025 to 300 €/kg Unat in 2050. This can be seen as the description of the *realistically optimistic scenario*, with scarcity of uranium becoming more and more real due to the fast development of worldwide nuclear generation capacity, inducing the use of uranium resources with a high extraction cost and more and more tensions on the uranium market.

(€/MWh$_e$)	**2025** **Technology: EPR representing Generation III**	**2050** **Technology: EPR representing Generation III**	**2050** **Technology: Breeding reactor - EFR or Generation IV type**
Fuel cycle cost	5.35	11.5	3.85
Uranium cost	1.6 (for a price of 62€/kg Unat)[34]	7.75 (for a price of 300€/kg Unat)	0
Conversion	0.25	0.25	0
Enrichment	1.5	1.5	0
Fuel production	0.75 [25]	0.75 [35]	1.17
Back end (reprocessing, waste disposal)	1.25	1.25	2.68

Table 7: Detail of fuel cycle costs for different future reactors types.
Sources of the figures: [ECONUC 2004], [EFR 1998]

For a price of 62 €/kg Unat, the uranium cost represents only 6 % (1.6 €/MWh$_e$) of the global electricity production cost, so that the electricity price is not very sensitive to an increase in the price of uranium. A 5 -fold increase of the natural uranium price (300€/kg Unat) would represent a 6.1 €/ MWh$_e$ increase in the cost of PWR generation cost.
Table 7 secondly shows that, from an economic perspective, such a raise of the uranium price could justify the appearance of Fast Breeder Reactors, which have a negligible uranium cost, but require, up to now, a 30 % increase of the investment as compared to the PWRs (increase of ~4.6 €/ MWh$_e$ for a 6% discount rate).

Remark: the calculation of the threshold uranium price above which Generation IV becomes competitive with current PWRs is very sensitive to the discount rate, the respective expected economic lifetime and the respective investment cost, so that the above values are just indicative. Depending on the different sources and assumptions, very different values may be found for the threshold: The minimum one sets the threshold for economic emergence of Generation IV at 130 €/kg Unat.

3.6.2. Other drivers of cost developments for NPPs

Cost development for nuclear power plants relies on several drivers:

- For evolutionary systems, cost development is a function of the technical evolutions, of the industrial, planning and building policy, and of the prevailing financial parameters. In fact, nuclear power plants require a building time of around 5 years, and this yields extra interest costs for the building time that have to be taken into account. As show in §2.4, the cost of a MWh$_e$ generated by a NPP is very sensitive to discount rate. The variability of available figures is often the result of this dependency.
- A literature survey on costs by PSI is available as an appendix (for a better readability of the document). It enables to state this variability of costs of nuclear.

[34] *At the beginning of 2007, spot prices on the market of uranium reach twice this figure (see appendix), making the uranium cost up to 2.5 €/ MWh$_e$. Hence one can even imagine scenarios with earlier tensions on uranium market.*

[35] *The figure given is an order of magnitude and does not represent the specific French situation. For the MOX fuel, the fuel production is more costly, but approximately compensated by the economy of uranium (see [ECONUC 2004]).*

- For Generation IV systems, the question is different, as these systems are likely to be very different from the existing. The objective of competitiveness defined by the GIF can be regarded as a target that Generation IV systems should achieve. In the meanwhile, the costs of the prototypes prefiguring what Generation IV FBRs could be quite high. This will be discussed below.

3.6.3. Discussion of the nominal asset life

Concerning plant lifetime, NPPs of the second generation were usually designed for 40 years of operation but this lifetime could be extended beyond 40 years with suitable management programmes including control of degradation processes, maintenance, repair and refurbishing and/or replacement of plant components and systems. In the USA, many existing NPPs are now authorized to operate till 60 years. The cost of this lifetime extension is less than the cost of building a new power plant.

New nuclear plants (it is the case for Generation III reactors) have a 60 years design lifetime.

For now, EPRs are designed on a technical life time of 60 years. Generation IV reactors will probably also be designed on the same base even if, in the above scenario, the Gen IV economic lifetime was set to 40 years by conservatism.

It is noteworthy that the EPR currently built in France has a "technical lifetime" of 60 years. While [OECD/IEA 2005] or [DGEMP 2003] make their calculations with an economic lifetime of 60 years, EDF has released figures stating an economic lifetime of 40 years as a precaution. One has to note that other parameters like the distribution of construction costs over the construction period also can explain differences between estimates.

3.6.4. Remarks on the comparability of the magnitude of investment costs from different studies

There are several investment cost estimates for future nuclear power plants available in the literature (e.g. [OECD/IEA 2006a], [OECD/IEA 2006b], [OECD/IEA 2005], [ECONUC 2004]; see also “Costs for future NPPs: a literature review by PSI” in the Appendix). In general, the magnitude of the investment costs is sensitive to several assumptions made, such as

- discount rate (around 2€/MWh for 1% more),
- economic life time (around 1€/MWh more for 20 years less),
- power of a single unit (according to [ECONUC 2004], there can be a ratio of 1/2 between specific costs of a 1350 MWe and of a 300 MWe unit),
- the number of units to be built (at least 100-200 €/kW less for a unit in a 10 units program compared with a First Of A Kind (FOAK) unit),
- but also currency-year and commercial operation date.

For this reason, it is difficult to compare costs from different publications with one another.

The reason for the selection of the cost data as used in this report is threefold: the level of detail provided, consistency of the data set and public availability of the data (see below). The high level of detail is needed to comply with the specific requirements of this task.

3.6.5. Costs for nuclear power plants – a summary for 2025

The costs provided below are derived from a literature review including following studies: for COD reference year 2025, [DGEMP 2003] data were selected because of the detailed explanations that are given in the reference paper. For COD reference year 2050, [GIF 2002], [EFR 1998], and [ECONUC 2004] data have been used.

In the Table 8 and Table 9, the main technical and cost data of the nuclear power generation for C.O.D. reference year 2025 are given. The original source is [DGEMP 2003], for a reactor type EPR series, and for base load generation with a Commercial Operation Date (C.O.D.) 2015. In the following columns, data have been adapted for NEEDS usage to account for reference currency and for the estimation of fuel cost in the year 2025 given in the Table 7 above.

Parameters	**Unit**	**Original Reference Data**[36]	**Data translated for NEEDS usage**
Currency (Cur.) reference year[37]		€ 2001 for DGEMP 2003	€ 2000
Discount rate		5	6
Technology		2015 (Technology: EPR – 10 units representing Generation III)	2025[38] (Technology: EPR – 10 units representing Generation III)
Size	MW_e	1590	1590
Economic life time	Years	60	60
Construction time[39]	Years	4.83	4.83
Availability	%	90.3[40]	90.3
1→ Overnight investment cost[41]	$Cur./kW_e$	1273.5[42]	1255.6
2→ interest cost during construction[43]	$Cur./kW_e$	215.7	259.9
3→ dismantling cost[44]	$Cur./kW_e$	6.5	3.4
4→ Total investment cost 4 = 1+2+3	$Cur./kW_e$	1496	1519
5→ Total Investment cost	**$Cur./MWh_e$**	**9.5**	**11.2**

Table 8: Detail of Investment costs for an EPR unit (reference technology for C.O.D 2025)

[36] *[DGEMP 2003]*

[37] *Conversion table is given in appendix.*

[38] *We assume a no evolution scenario for investment and O&M costs.*

[39] *Construction time: 67 months for the First unit Of A Kind (FOAK) -, 57 months for the following units.*

[40] *With 35% availability between grid connection and C.O.D. (assumption : 1 year) and 72.3% availability the year after C.O.D. [DGEMP 2003]*

[41] *Including construction and possible engineering cost, pre-operation cost, risks on planning.*

[42] *In [DGEMP 2003] decomposition is the following: construction cost engineering cost + pre-operation cost + risks on planning.*

[43] *[DGEMP 2003] interest cost during construction is 215.7 €/kW$_e$ for a 5% discount rate but no expense schedule is given.*

[44] *Dismantling cost is estimated as 15% of the total investment cost and expense schedule is similar to [DGEMP2003]'s.*

Parameters	Unit	Original Reference Data[45]	Data translated for NEEDS usage
5→ Total Investment cost	**Cur./MWh$_e$**	**9.5**	**11.2**
Fixed O&M cost	Cur./kW$_e$/y	50.9[46]	50.1
Variable O&M cost	Cur./MWh$_e$	0.61	0.60
6→ Total O&M cost	**Cur./MWh$_e$**	**7.3**	**7.2**
7→ R&D cost	**Cur./MWh$_e$**	**0.6**	**0.6**
8→ Fuel cost included up and downstream	**Cur./MWh$_e$**	**4.4**	**5.3[47]**
Levelised cost of generated electricity = 5+6+7+8	**Cur./MWh$_e$**	**21.8**	**24.4**

Table 9: Costs of generated electricity for an EPR unit (reference technology for C.O.D. 2025)

3.6.6. Costs for Generation IV nuclear power plants – a summary for 2050

Generation IV reactor studies are still conceptual studies: it is neither possible to give an accurate cost yet nor to predict the best solution that will be developed. The choice of the future reactor will be based on the consideration of techno-economic criteria (safety, availability, investment, operation costs, etc.).

With a 6% discount rate, the cost objective could be in 2050 to reach the same investment and O&M costs than for the EPR (in the case of industrial development), in constant currency.

Today, there is no available Generation IV technology, but the nearest concept is the sodium fast breeder reactor. It is not currently competitive with PWRs at present natural uranium price because of a too high initial investment cost. The most advanced sodium FBR project in France was the EFR (European Fast Reactor; we call it a "pre Generation IV"). EFR is a concept which has been defined in order to summarize the experience learnt from SuperPhenix. A real Generation IV breeder reactor would feature some technological breakthroughs that would make it more advanced than EFR.

As the table will show, in the conditions of the *Realistically Optimistic Scenario*, the EFR -European Fast Reactor could be competitive for a C.O.D in 2050.

The figures related to Reference NPP Technology (Generation III) for 2025 - given in the last column of Table 8 and Table 9 - are reported in the first column of the following table as Reference Technology (Generation III) for 2050, with the exception of fuel cost figure which is taken according to Table 7 projection, in conformity with the *Realistically Optimistic Scenario*. A no evolution scenario is assumed for investment and O&M costs in the period 2025-2050.

These figures are compared with:

- Firstly an already available pre GEN IV FBR technology: the so-called European Fast Reactor (EFR), with an investment cost 30% higher than the GEN III technology,

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[45] *[DGEMP 2003]*

[46] *With the following decomposition for O&M fixed cost: 50.9 = 35.1 (specific O&M cost out of taxes) + 15.8 (taxes).* ***If we remove taxes, the levelised cost of generated electricity is 2 €$_{2001}$/MWh$_e$ less, i.e. 19.8 €$_{2001}$/MWh$_e$ in the reference data and 22.4 €$_{2000}$/MWh$_e$ in data translated for NEEDS purpose data.*** *Moreover, the effect of post-operating cost (150 k€ spread over 3 years) can be considered as negligible.*

[47] *See Table 7 for details.*

- Secondly with what a GEN IV FBR reference technology could be in 2050 by assuming progress on the investment and the O&M cost (trend to reach same level as Generation III).

Table 10 shows that in 2050, under the conditions of the *Realistically Optimistic Scenario*, there could have been emergence of Generation IV technology since the conditions of competitiveness of Fast Breeder Reactors would have been reached.

Parameters	**Unit**	**2050**	**2050**	**2050**
Currency (Cur.)		€ 2000	€ 2000	€ 2000
Discount rate		6	6	6
Technology		Generation III (EPR – 10 units)	pre GEN IV (EFR=already available)	2050 Gen IV (Gen IV objectives = competitive with EPR)
Size	MW_e	1590	1450	1450
Economic life time	Years	60	40	60[48]
Construction time	Years	4.83	5.5	5
Availability	%	90.3	90	Expected at least 90% (best available technology)
1→ Overnight investment cost[49]	Cur./kW_e	1255.6	PWR (EPR) + 30%	~PWR (EPR)
2→ interest cost during construction	Cur./kW_e	259.9	PWR (EPR) + 30%	~PWR (EPR)
3→ dismantling cost[50]	Cur./kW_e	3.4	PWR (EPR) + 30%	~PWR (EPR)
4→ Total investment cost 4 = 1+2+3	Cur./kW_e	1519	PWR (EPR) + 30%	~PWR (EPR)
5→ Total Investment cost	**Cur./MWh_e**	**11.2**	**15.8**	**11.2**
Fixed O&M cost	Cur./kW_e/y	Same as EPR in 2025	Same as PWR (EPR) in 2025	Same as PWR (EPR) in 2025
Variable O&M cost	Cur./MWh_e	Same as EPR in 2025	Same as PWR (EPR) in 2025	Same as PWR (EPR) in 2025
6→ Total O&M cost	**Cur./MWh_e**	**7.2**	**7.3**	**7.2**
7→ R&D cost	**Cur./MWh_e**	**0.6**	**0.6 (~EPR)**	**0.6 (~EPR)**
8→ Fuel cost incl. up and downstream	**Cur./MWh_e**	**11.5**	**3.85**	**3.85**
LCOGE = 5+6+7+8	**Cur./MWh_e**	**30.5**	**27.5**	**22.9**

Table 10: Indicative nuclear electricity production cost decomposition, for a PWR of EPR style and for Generation IV fast breeder reactors

[48] *An ELT larger than 40 years is expected which is set to 60 years.*

[49] *Including construction and possible engineering cost, pre-operation cost, risks on planning.*

[50] *Dismantling cost is estimated as 15% of the total investment cost (1+2)*

4. Specification of the technology configurations for NEEDS studies

In Table 11, the reference technologies are specified for the scenario-year combinations as needed for RS1a purposes of the NEEDS project. All technologies will be described in more detail below.

Table 11: Reference technology by scenario and year

Scenario	2000	2025	2050
Pessimistic	N4 *)	EPR	EPR
Realistically optimistic	N4 *)	EPR	Gen IV FBR **)
Very optimistic	N4 *)	EPR	Gen IV FBR **)

EPR: European Pressurized Reactor; *FBR*: sodium cooled Fast Breeding Reactor, 60 year life time; *Gen IV*: Nuclear Power Plant of the 4th generation; *N4*: Pressurized Water Reactor of N4 type with 1450 MWe
LCI data corresponding to *) 1000 MWe and **) existing EFR, 40 year life time

4.1. Specifications for 2000

4.1.1. Situation in 2000

In 2000, the European nuclear fleet is mainly composed of Light Water Reactors. Among them, the PWR is the most common type of reactor since it represents about 80% of the European installed reactors. Hence, PWR is assumed to be significantly representative for the current situation.

Fuel enrichment is performed by gaseous diffusion, with a 3.8% U235 enrichment. Diffusion is accomplished by EURODIF which is considered in the ecoinvent database to be supplied by nuclear power. Moreover, plutonium resulting from spent fuel is mono-recycled in MOX assemblies. These assumptions reflect the French fuel cycle: indeed, France represented the largest nuclear country within EU25.

4.1.2. Technical specifications for LCI

The table 12 gives an overview on the reference nuclear power plant for the current situation

Parameter	Unit	Year 2000
	-	**Pressurized Water Reactor of N4 series (N4)**
Size	MW_{el}	1,000
Life time	Y	40
Enrichment process	-	Gaseous diffusion
Main data sources for environmental data	-	ecoinvent database R.Dones, 2003

Table 12: Overview of the reference nuclear power plant for the 2000 situation

4.2. Specifications for 2025

A major trend for the nuclear industry during the first half of the century could be the extension of the life span of current nuclear power plants, and simultaneously the deployment of Generation III reactors, either to replace ageing reactors or to develop nuclear electricity production as a response to the foreseen increased energy consumption under a constraint on Climate Change and scarcity of fossil fuels.

4.2.1. Situation in 2025

In Europe, many currently operated nuclear plants should still be in operation in 2025; they should then account for the largest share of nuclear electricity generation. But considering a reasonably dynamic nuclear expansion, Generation III large-scale deployment is likely to begin around 2020 and we assume that it would be the "best available" technology for new plants in 2025. In fact, two first of a kind EPRs are already under construction in Finland, and in Flamanville, France. As the EPR is a good representative of the Generation III evolutionary systems, with the advantage that data should be available for our study, we chose it for our study.

This choice of the EPR is common to all scenarios: what will vary is the number of built EPRs, and therefore the investment cost. For the purpose of NEEDS, we will have to choose an assumption, as the model in RS 2a does not take into account such variations.

Enrichment by ultra-centrifugation is the most representative technology in Europe, as enrichment by gaseous diffusion has been ruled out in France.

The deployment of Generation III reactors is in progress, either to replace ageing Generation II reactors, or to increase nuclear energy production. The nuclear technology representing the average of installed plants is still Generation II reactors.

4.2.2. Specifications of study system

The study system for year 2025 is a PWR of EPR type in a nuclear fuel cycle involving only ultra-centrifugation.

The main characteristics are summarized in Table 13:

Parameter	Unit	Year 2025
	-	**European Pressurized Reactor (EPR)**
Size	MW_{el}	1,590
Life time	y	60
Enrichment process	-	Ultra-centrifugation
Main data sources for environmental data	-	EDF ecoinvent database R.Dones, 2003

Table 13: Overview of the reference nuclear power plant for the 2025 situation

Specifications for the cycle:

Ultra-centrifugation having replaced gaseous diffusion, the fuel enrichment in U235 will be 4.9 %, and the discharge burn up 60,000 MWj/t. UOX spent fuel will be reprocessed, fission products and minor actinides will be vitrified, and plutonium will be mono recycled in MOX assemblies. Spent MOX fuel will be kept in interim storage facilities.

4.3. Specifications for 2050

4.3.1. Pessimistic scenario

In the pessimistic scenario, nuclear energy is not developing enough to yield the emergence of Generation IV. The study system is an EPR, like in 2025.

4.3.2. Nuclear optimistic scenario: we need a Generation IV reactor, but which one?

In 2050, Generation IV nuclear reactors could be developed enough to enable the operation of industrial plants delivering power to Europe, in such a way that we can consider Generation IV as an “emerging technology” for the purpose of the NEEDS LCI study. Even in this "nuclear reasonably optimistic scenario" it may still be necessary to construct EPRs in 2050. **In 2050 the nuclear fleet is entirely composed of Generation III and emerging Generation IV reactors.**

This being stated, we are facing two problems: Which kind of Generation IV technology should we choose for our study? – and more particularly, Should we consider the Very High Temperature Reactor for hydrogen production as another Generation IV technology available in 2050, or not?

The following paragraphs aim at answering these questions:

The first phase of R&D studies on Generation IV systems is a viability phase, aimed at resolving key feasibility and proof-of-principle issues. It has just started, and will go on for years before being able to decide whether to undertake large-scale technology developments for any of the concepts studied. As for today, it is not possible to foresee which FBR technology will emerge from this R&D process and be deployed in a few decades. And of course no data are available for our LCI at this very preliminary stage: for instance, we don’t even know what could be the fuel form and composition for a Gas Cooled Fast Reactor. Not to mention the fuel cycle facilities, which are strongly linked to the type of reactor and fuel.

Nevertheless, **sodium cooled FBRs have already been extensively studied**, and prototypes built and operated. So for very pragmatic reasons, we suggest choosing the **European Fast Reactor (EFR, 1450 MWe, pool type, with plutonium recycling fuel cycle [EFR 1998]) as a good representative of FBRs** for our study purposes**. All the data we need, regarding the reactor as well as each of the fuel cycle facilities, are available for the EFR**. Of course, Generation IV FBRs will perhaps use another coolant than the sodium used by EFRs; or, even if sodium cooled, they will present significantly different features. **But as we already underlined, LCI results will likely not be too strongly impacted by the type of FBR chosen for the study.**

Regarding the Very High Temperature Reactor for hydrogen production, which is a promising Generation IV concept, we are facing the same difficulty as for the Generation IV FBR: the viability of the reactor technology has not been proved yet, as it relies on the possibility to find materials able to be used at a temperature of around 1000°C, and many uncertainties remain.

Furthermore, the thermo-chemical cycles considered for hydrogen production because of their theoretical high efficiency (~50 %), like the Sulphur-Iodine cycle, will certainly raise similar concerns regarding materials: the working fluids involved in these cycles should be very corrosive, and only ceramics could resist, but their ability to be produced in the form of components of a large size has not been proven yet. High temperature electrolysis will certainly face the same concerns regarding materials and ceramics: as the composition of these materials is not known yet, it is not possible to make a LCI study for this step of hydrogen production.

Classical alkaline electrolysis could be a possibility for a nuclear hydrogen generation LCI study, in the same way that it will be used for hydrogen production channels using renewables, but the high temperature of the VHTR is of no interest then.

As a conclusion: unlike for the FBR, we unfortunately don’t have at our disposal any consistent set of data to carry out a LCI-type study of a VHTR (reactor + hydrogen production plant). And it doesn’t seem possible to get accurate information about a very innovative system, which is at a very early stage of R&D, within the timeframe of NEEDS RS 1a. We judge it very premature to take the VHTR into account in our LCI-type study, and we prefer to concentrate our efforts for the 2050 milestone on the FBR, as we have accurate data.

So we can consider that the FBR (fast breeder) will not be the only technology available by that time, but this will be the only one considered for LCI.

4.3.3. Technical specifications for LCI

The study system for year 2050 is a FBR of EFR type (European Fast Reactor). Plutonium is recycled in EFR.

The chosen Generation IV FBR reactor is a sodium cooled reactor, power 1450 MW. The nearest industrial description of such a reactor available for LCI study today is the EFR, therefore, the LCI study will be performed on an EFR (European Fast Reactor). In comparison with EFR, a “real” Generation IV FBR should be easier to operate, less costly and with an enhanced safety. While a 60 year life time is assumed for the costs (see last column of Table 10), the LCI data are based on a 40 year life time (see Table 14).

The EFR has been precisely described in [Lefèvre 1996].

Its main characteristics are summarized in Table 14:

Parameter	Unit	Year 2050
	-	European Fast Reactor (EFR)
Size	MW_{el}	1,450
Life time	y	40
Fuel cycle	-	closed – recycling of Pu
Main data sources	-	EDF 2000 (LCA study of an EFR plant, 2000)

Table 14: Overview on the reference nuclear power plant for the 2050 situation

4.3.4. Discussion of this choice

This choice of a reactor type results from pragmatic considerations about LCI, on the one hand, and from a vision of the future of nuclear energy, on the other hand.

This vision is the following:

Unlike Generation III, which is very close to the current situation and technologies (with respect to the concerns addressed here, i.e. LCA of nuclear electricity generation), the Generation IV represents a technical breakthrough, with important technological changes affecting not only the reactors but also the entire fuel cycle, and requires an important and ambitious R&D program.

The time horizon for Generation IV will therefore be the result of several drivers: concerns about nuclear sustainability and progress will act as drivers to accelerate the emergence of Generation IV, but technical and industrial constraints will act as inertia because of the long project and construction time. Therefore, in 2050, nuclear energy generation is likely to be in a transitory situation, Generation III still being predominant in the fleet operated then. HTR could also be present depending on the real market for nuclear industrial heat and nuclear hydrogen.

The drivers we presently acknowledge as being the most important are related to fuel management: efficient use of uranium resources, fuel regeneration, minimization of waste.

It is still possible, though, that other drivers will become much more important and finally lead to the emergence of completely different nuclear systems, like high temperature reactors (HTR – VHTR) for instance.

Therefore, we want to stress upon the pragmatic reasons that lead to the choice of the sodium cooled FBR for NEEDS: availability of data and limited time planned for this task in the NEEDS project. The chosen systems are not comprehensive regarding future possible nuclear systems.

5. Life Cycle Inventory data

For each technology to be taken into account, the different processes were compiled according to the requirements of RS1a regarding the data structure to be delivered. Such requirements lead to the following two-level structure (see figure 1).

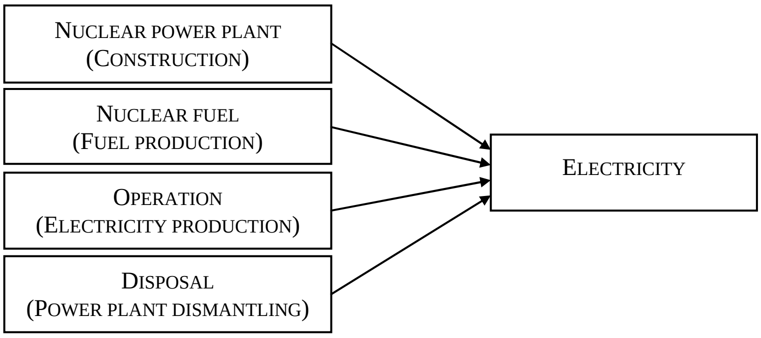

Figure 6 Main life cycle phases of nuclear electricity according to the scheme adopted for integration within NEEDS

Quality and relevance of the data represent the main criteria of selection for this study, as essential conditions of the consistency of the LCA results. For each reference year, the LCI data aim at being representative for the state of the art or the “best available technology” within the European fleet. This target corresponds to the choice of the following three milestone technologies.

2000: Pressurized Water Reactor (PWR)

For year 2000, the Swiss ecoinvent database was chosen insofar as it represents the best available public database. Thus, the PWR model is based on data from Dones 2003, extracted from ecoinvent database.

The most recently installed nuclear power plants in Europe (closest to reference year 2000) belong to the 1300-1400 MW class (Convoy, N4). However, although they correspond to plants belonging to the 1000 MW class, ecoinvent data turned out to be conservative for the 1300-1400 class. For the purpose of modelling, they can therefore be assumed to be representative for other PWRs within Europe for the purpose of such a LCA approach.

As mentioned previously, selected processes were compiled in accordance with the common format decided within RS1a for the different electricity systems (see Figure 7).

The *Operation* process was chosen to be suitable for the reference system for the current situation, particularly regarding a 3.8% fuel enrichment rate. The Operation process, corresponding to such specifications within the ecoinvent database, is based on Swiss data for one specific plant for both material and transport requirements and on all French PWRs for emissions during operation?. The French process was selected because of the lack of appropriate data for the UCTE situation. However, from a LCA point of view, LWRs are about the same worldwide if particular cases are excluded, such as the existence of cooling tower or specific site conditions. Hence, in spite of such a choice, results are assumed to be consistent with the assumption of best available technology.

The back-end part of the fuel cycle is considered to be part of the Operation process, in accordance with the approach taken by ecoinvent, in which all the nuclear spent fuel is sent to the reprocessing plant.

Emissions during both *Building* and *Disposal* of the power plant were taken from the ecoinvent database too. Data are extrapolated from Swiss data for one specific plant which belongs to the 1000 MW class. In the framework of the scheme adopted for modelling within NEEDS, the Disposal process only includes dismantling (i.e., no releases from deposited spent fuel).

The *Fuel* process is subdivided into two sub-phases: the production of uranium oxide fuel (UOX, with a 3.8% U235 enrichment) and mixed oxide fuel (MOX). Both of them are available in the ecoinvent database, corresponding to North American and European conditions. Thus, the nuclear fuel process results from combining MOX fuel element production and uranium enriched to 3.8%.

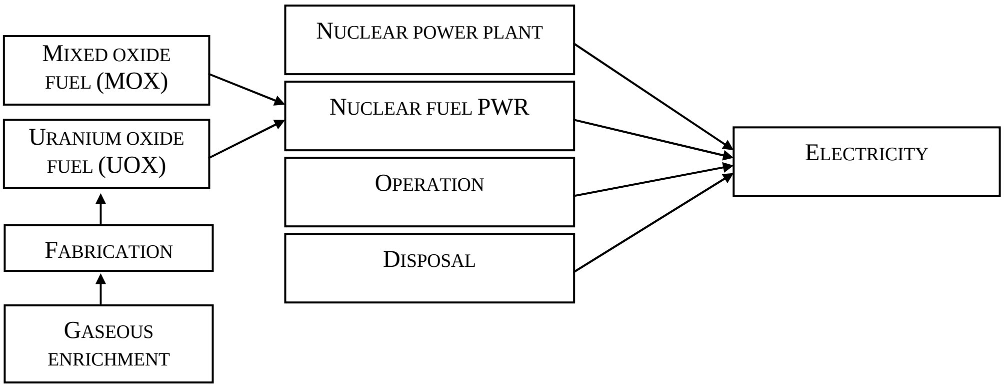

Figure 7 Main life cycle phases of pressurized water reactors (PWR) according to the scheme adopted for integration within NEEDS

All the data can be assumed to be representative for other pressure water reactors of the same class in Europe as regards the LCA approach.

2025: European Pressurized Reactor (EPR)

For year 2025, the study system is a PWR of EPR type in a nuclear fuel cycle involving only centrifugation. The collected data correspond to the French EPR project in Flamanville. They are extracted from the following public documents : *“Rapport préliminaire public de sûreté"* and *“Dossier d’autorisation de création de l’EPR Flamanville3”*. Where missing, data were extracted from the Swiss ecoinvent database (after Dones 2003).

Selected processes were compiled in accordance with the common format decided within RS1a for the different electricity systems (see Figure 8).

The *Operation* process is mainly based on French data, especially for radioactive emissions (both to air and to water) and for nuclear wastes. Use was made of some (generic, i.e. not-specific) ecoinvent data because of lack of original data. Appropriate extrapolation rules were applied (such as???).

The back-end part of the fuel cycle is considered to be part of the Operation process, in accordance with the approach taken by ecoinvent, in which all the nuclear spent fuel is sent to the reprocessing plant.

Emissions during both *Building* and *Disposal* of the power plant are based on data from the Flamanville power plant and ecoinvent data by default. In this latter case, extrapolations are made with ratios based on concrete or steel consumptions.

The *Fuel* process is subdivided into two sub-phases: the production of uranium oxide fuel (UOX, with a 4.9 % U235 enrichment) and mixed oxide fuel (MOX). MOX is available in the ecoinvent database, corresponding to North American and European conditions. UOX is adapted – with 4.9 % enrichment rates - from U enriched 4.2%, centrifugal enrichment, at nuclear fuel fabrication plant (Switzerland).

Thus, the nuclear fuel process results from combining MOX fuel element production and uranium enriched to 4.9%.

All these data can be assumed to be representative for other pressure water reactors of the same class in Europe as regards LCA approach.

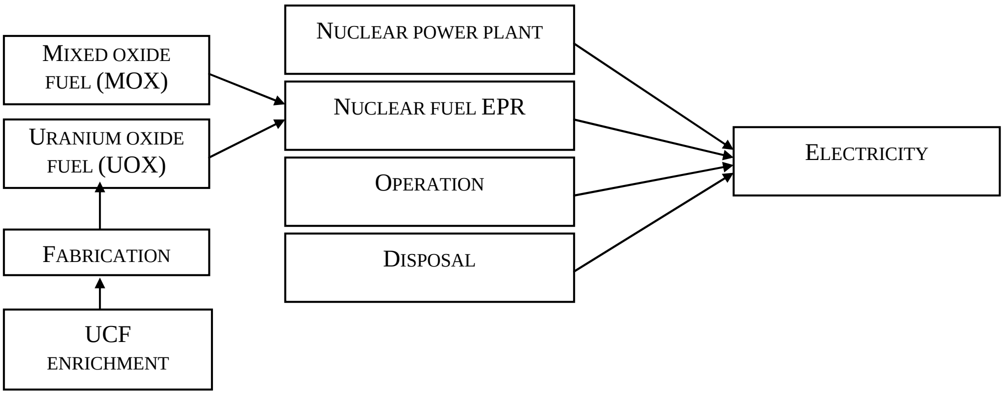

Figure 8 Main life cycle phases of European Pressurized water Reactor (EPR) according to the scheme adopted for integration within NEEDS

2050: European Fast Reactor (EFR)

In 2050, no data are available for a LCI study at this early stage of development as regards the European Fast Reactor. However, EDF has taken part in the French work on the future nuclear fuel end. A specific work was done on the data for EFR, in collaboration with EDF experts involved in the Superphenix project.

This study provided the original data for *Operation* and *Building*. Given that no data are available for the *Disposal* part, the data are extrapolated from the ones for PWR, by employing a ratio of the respective concrete consumptions (i.e., EFR = 1.5 x PWR). The *Fuel*, which consists of a mix of recycled plutonium and depleted uranium, is modelled after Dones, 2003 *(« MOX fuel element for EFR, at nuclear fuel fabrication plant »*, ecoinvent).

As for the other reference NPPs, selected processes were compiled in accordance with the common format decided within RS1a for the different electricity systems (see Figure 9).

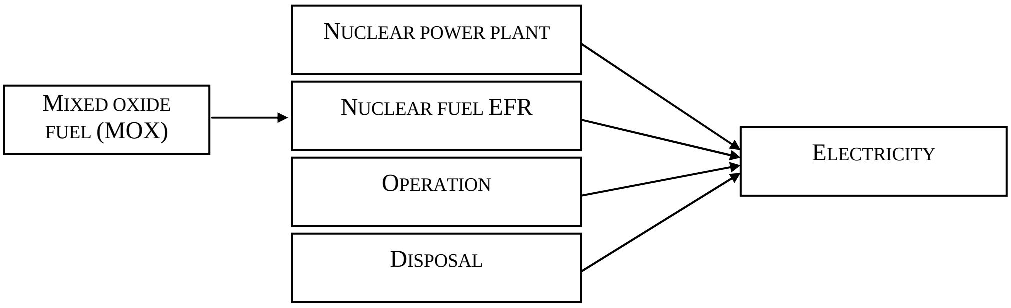

Figure 9 Main life cycle phases of European Fast Reactor (EFR) according to the scheme adopted for integration within NEEDS

Note that there are some deviations between the reference technologies as used for the derivation of cost data and of LCI data in the case of the 2000 PWR of the N4 series and the 2050 Gen IV reactor (see sections 4.1.2 and 4.3.3, respectively).

5.1. Material input

Table 15 shows the consumption of concrete, reinforcing steel and steel for the three nuclear reference technologies.

Input	*Unit (/kWh$_{el}$)*	Present	2025	2050
Concrete, normal, at plant	m^3	6.41E-07	5.02E-08	6.71E-07
Reinforcing steel, at plant	kg	1.28E-04	6.03E-05	1.07E-04
Steel, low-alloyed, at plant	kg	2.11E-05	1.24E-05	1.27E-05

Table 15: Material flows (concrete and steel) required for building of nuclear power plants

5.2. Key emissions and land use

As a result of work carried out in RS1a WP1, a “minimum air pollutant list” to be used for the external cost assessment was defined between RS 1a and RS 1b. The emissions shown in Table 16 are an excerpt of this minimum list. This table shows the Life Cycle Inventories (LCI) of selected elementary flows including land use for 4 types of energy systems (i.e., N4 PWR, EPR, EFR and a mixture of these as specified below the table), at three points in time (i.e., 2000, 2025 and 2050) for 5 different scenarios. The assumptions of these scenarios concern the composition of the UCTE and, thus, the emissions related to the electricity used by processes for which no specific information on a particular power technology is available. These scenarios differ particularly according to assumptions regarding greenhouse gas emission reduction targets (i.e., Business As Usual (BAU) or 440 ppm CO_2-equivalent limit) and the way these are achieved (e.g., by means of renewables) as well as the development of a specific class of technology as used throughout this document (i.e., pessimistic (PE), realistic optimistic (RO) and very optimistic (VO)). The scenarios translate into a certain composition of the nuclear power park in the UCTE mix (see footnote to Table 16). The associated emissions of a unit of electricity from the UCTE were assessed by ESU services in the frame of RS1a WP5. All of the LCI data are referring to one kilowatt-hour electricity delivered to the grid.

Table 16: Life cycle inventory of key emissions and land use for the reference plant (PWR, present situation, EPR, 2025 situation, EFR, 2050 situation)

Parameter	Path	Unit	Scenarios*	2000		2025			2050		
				PWR	MIX*	PWR	EPR	MIX*	EPR	EFR	MIX*
				/kWh$_{el}$	/kWh$_{el}$	/kWh$_{el}$	/kWh$_{el}$	/kWh$_{el}$	/kWh$_{el}$	/kWh$_{el}$	/kWh$_{el}$
CO_2, fossil	air	kg	Sc1	5.91E-03	**5.91E-03**	5.58E-03	4.73E-03	**5.33E-03**	4.72E-03	-	**4.72E-03**
			Sc2			5.27E-03	4.45E-03	**5.02E-03**	4.05E-03	-	**4.05E-03**
			Sc3			5.18E-03	4.39E-03	**4.95E-03**	3.91E-03	8.19E-04	**3.76E-03**
			Sc4			5.05E-03	4.29E-03	**4.82E-03**	3.78E-03	7.40E-04	**3.63E-03**
			Sc5			-	-	-	-	-	-
CH_4, fossil	air	kg	Sc1	1.02E-05	**1.02E-05**	1.04E-05	8.19E-06	**9.73E-06**	8.18E-06	-	**8.18E-06**
			Sc2			1.02E-05	8.04E-06	**9.57E-06**	7.69E-06	-	**7.69E-06**
			Sc3			9.27E-06	7.24E-06	**8.66E-06**	5.69E-06	2.04E-06	**5.51E-06**
			Sc4			8.17E-06	6.31E-06	**7.61E-06**	4.90E-06	1.73E-06	**4.74E-06**
			Sc5			-	-	-	-	-	-
NO_x	air	kg	Sc1	3.05E-05	**3.05E-05**	2.84E-05	2.48E-05	**2.73E-05**	2.47E-05	-	**2.47E-05**
			Sc2			2.82E-05	2.45E-05	**2.71E-05**	2.50E-05	-	**2.50E-05**
			Sc3			2.76E-05	2.41E-05	**2.65E-05**	2.36E-05	2.66E-06	**2.26E-05**
			Sc4			2.73E-05	2.39E-05	**2.63E-05**	2.34E-05	2.53E-06	**2.24E-05**
			Sc5					-			-
NMVOC	air	kg	Sc1	7.35E-06	**7.35E-06**	7.26E-06	6.49E-06	**7.03E-06**	6.47E-06	-	**6.47E-06**
			Sc2			7.37E-06	6.59E-06	**7.14E-06**	6.55E-06	-	**6.55E-06**
			Sc3			7.32E-06	6.54E-06	**7.08E-06**	6.46E-06	7.35E-07	**6.17E-06**
			Sc4			7.26E-06	6.50E-06	**7.03E-06**	6.40E-06	7.04E-07	**6.12E-06**
			Sc5			-	-	-	-	-	-
SO_2	air	kg	Sc1	2.74E-05	**2.74E-05**	2.30E-05	2.00E-05	**2.21E-05**	2.00-05	-	**2.00E-05**
			Sc2			2.28E-05	1.98E-05	**2.19E-05**	1.98E-05	-	**1.98E-05**
			Sc3			2.22E-05	1.94E-05	**2.14E-05**	1.89E-05	2.53E-06	**1.81E-05**
			Sc4			2.17E-05	1.91E-05	**2.09E-05**	1.84E-05	2.23E-06	**1.76E-05**
			Sc5			-	-	-	-	-	-
PM 2.5-10	air	kg	Sc1	2.39E-06	**2.39E-06**	2.33E-06	1.65E-06	**2.13E-06**	1.65E-06	-	**1.65E-06**
			Sc2			2.33E-06	1.65E-06	**2.12E-06**	1.66E-06	-	**1.66E-06**
			Sc3			2.23E-06	1.58E-06	**2.04E-06**	1.52E-06	7.73E-07	**1.48E-06**
			Sc4			2.13E-06	1.52E-06	**1.95E-06**	1.47E-06	7.43E-07	**1.43E-06**
			Sc5			-	-	-	-	-	-
PM 2.5	air	kg	Sc1	4.68E-06	**4.68E-06**	4.37E-06	3.51E-06	**4.11E-06**	3.51E-06	-	**3.51E-06**
			Sc2			4.34E-06	3.49E-06	**4.09E-06**	3.53E-06	-	**3.53E-06**
			Sc3			4.21E-06	3.39E-06	**3.97E-06**	3.29E-06	7.47E-07	**3.16E-06**
			Sc4			4.10E-06	3.32E-06	**3.86E-06**	3.27E-06	7.29E-07	**3.14E-06**
			Sc5			-	-	-	-	-	-
Carbon-14	air	kBq	Sc1	5.09E-02	**5.09E-02**	5.09E-02	6.57E-02	**5.53E-02**	6.56E-02	-	**6.56E-02**
			Sc2			5.09E-02	6.56E-02	**5.53E-02**	6.57E-02	-	**6.57E-02**
			Sc3			5.09E-02	6.56E-02	**5.53E-02**	6.57E-02	1.20E-02	**6.30E-02**
			Sc4			5.09E-02	6.56E-02	**5.53E-02**	6.57E-02	1.20E-02	**6.30E-02**
			Sc5			-	-	-	-	-	-
Iodine-129	air	kBq	Sc1	5.29E-05	**5.29E-05**	5.29E-05	3.99E-05	**4.90E-05**	3.99E-05	-	**3.99E-05**
			Sc2			5.29E-05	3.99E-05	**4.90E-05**	3.99E-05	-	**3.99E-05**
			Sc3			5.29E-05	3.99E-05	**4.90E-05**	3.99E-05	1.24E-05	**3.85E-05**
			Sc4			5.29E-05	3.98E-05	**4.90E-05**	3.99E-05	1.24E-05	**3.85E-05**
			Sc5			-	-	-	-	-	-
Radon-222	air	kBq	Sc1	7.76E+02	**7.76E+02**	7.76E+02	7.50E+02	**7.68E+02**	7.50E+02	-	**7.50E+02**
			Sc2			7.76E+02	7.50E+02	**7.68E+02**	7.50E+02	-	**7.50E+02**

Parameter	Path	Unit	Scenarios*	2000		2025			2050		
				PWR	MIX*	PWR	EPR	MIX*	EPR	EFR	MIX*
				$/kWh_{el}$	$/kWh_{el}$	$/kWh_{el}$	$/kWh_{el}$	$/kWh_{el}$	$/kWh_{el}$	$/kWh_{el}$	$/kWh_{el}$
			Sc3			7.76E+02	7.50E+02	**7.68E+02**	7.50E+02	4.32E-01	**7.13E+02**
			Sc4			7.76E+02	7.50E+02	**7.68E+02**	7.50E+02	4.29E-01	**7.13E+02**
			Sc5			-	-	-	-	-	-
Land use	resource	m^2a	Sc1	4.57E-04	**4.57E-04**	4.89E-04	2.55E-04	**4.18E-04**	2.58E-04	-	**2.58E-04**
			Sc2			4.85E-04	2.51E-04	**4.15E-04**	2.47E-04	-	**2.47E-04**
			Sc3			4.83E-04	2.50E-04	**4.13E-04**	2.40E-04	5.86E-05	**2.31E-04**
			Sc4			4.82E-04	2.48E-04	**4.12E-04**	2.42E-04	6.03E-05	**2.33E-04**
			Sc5			-	-	-	-	-	-

** Note the different nuclear power plant shares in the electricity mix according to the different scenarios :*

Sc1 - PE BAU : 2000: 100% PWR 2025: 70% PWR and 30% EPR 2050: 100% EPR
Sc2 - PE 440ppm : 2000: 100% PWR 2025: 70% PWR and 30% EPR 2050: 100% EPR
Sc3 - RO 440ppm: 2000: 100% PWR 2025: 70% PWR and 30% EPR 2050: 95% EPR and 5% EFR
Sc4 - VO 440ppm : 2000: 100% PWR 2025: 70% PWR and 30% EPR 2050: 95% EPR and 5% EFR
Sc5 - VO Renew : 2000: 100% PWR 2025 &2050: no nuclear in the electricity-mix

Given that none of the nuclear power plant types described in this report will exist over the whole time span for which the assessment is carried out, two comparisons of the evolution of the LCI are provided below: first, a comparison of the LCI of the nuclear mix in the UCTE over time; second, a comparison of the LCI data per reference technology over the different time horizons (i.e., N4 PWR in 2000 and 2025, EPR in 2025 and 2050, and EFR in 2050)

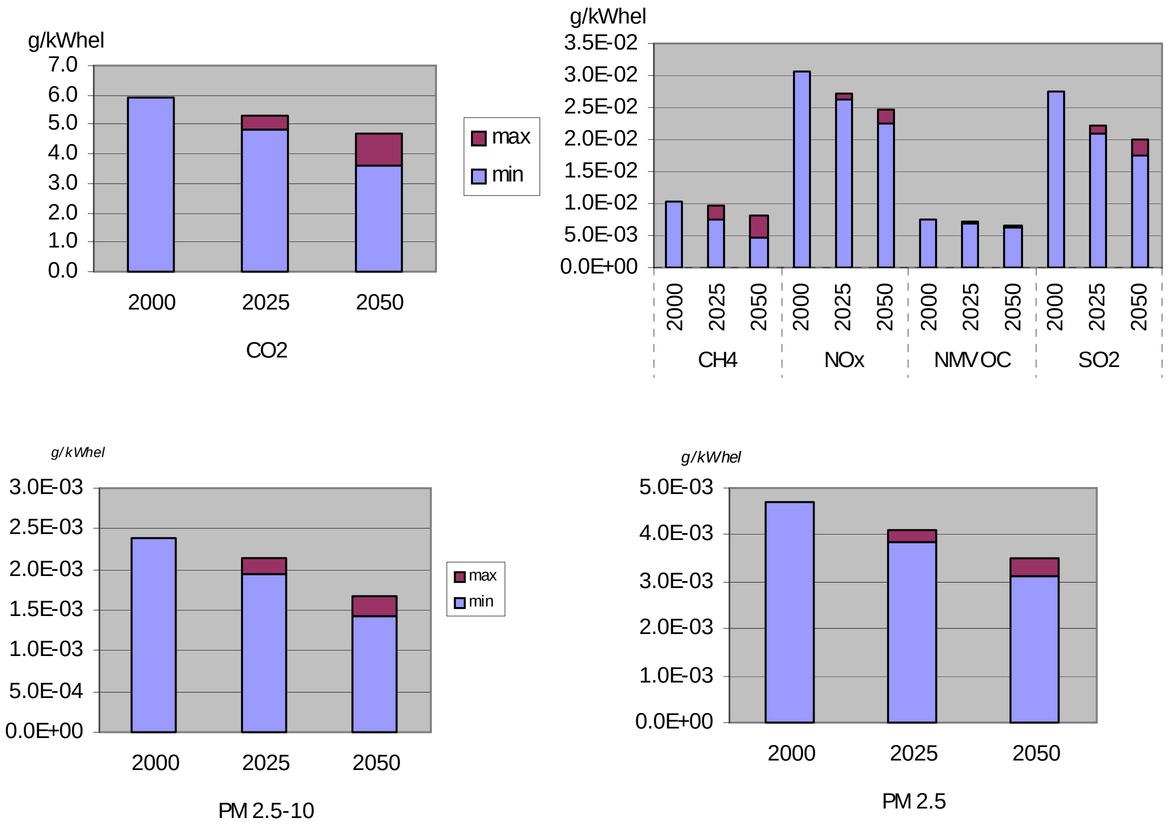

Figure 10 Development over time of non-radioactive emissions for a mixed nuclear kWh_{el}
(minimum and maximum values for each base year correspond to the range of all considered scenarios but scenario 5)

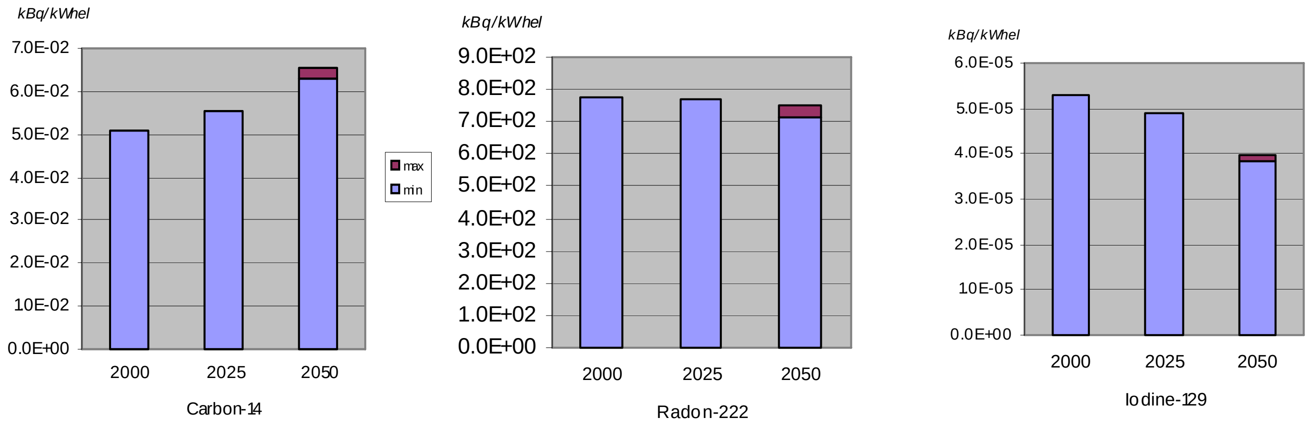

Figure 11 Development over time of radioactive emissions for a mixed nuclear kWh_{el}
(minimum and maximum values for each base year correspond to the range of all considered scenarios but scenario 5)

The figures 10 and 11 show the evolution of the emissions of a mixed nuclear kWh_{el}, with minimum and maximum values (depending on the scenarios considered) for each base year. As may have been expected, the highest emissions result under the pessimistic scenarios (PE BAU and PE 440 ppm) whereas the lowest emissions are regularly obtained under the very optimistic scenario (VO 440 ppm). Only the radionuclide emissions that stem exclusively from the nuclear fuel cycle remain unchanged for any given mix of power plants (in 2025: EPR and PWR, in 2050: only EPR in the pessimistic case and EPR and EFR in the optimistic realistic and very optimistic cases). This is because the influence of the emissions from the UCTE mix is negligible for radionuclide releases in the life cycle of nuclear power plants.

Most of the graphs show that there will be a decrease of LCI values, from 2000 to 2050. This decrease is directly connected to the same decrease of LCI values from PWR to EPR, then EFR (see below).

The change in magnitude between the *min* and *max* values (depending on scenarios) is rather small. The variations do not exceed 30 % (for CO_2 in 2050).

C14 is the only exception; it is a particular case, because EcoInvent does not give any data for this flow (see further discussion with respect to specific nuclear power plants below).

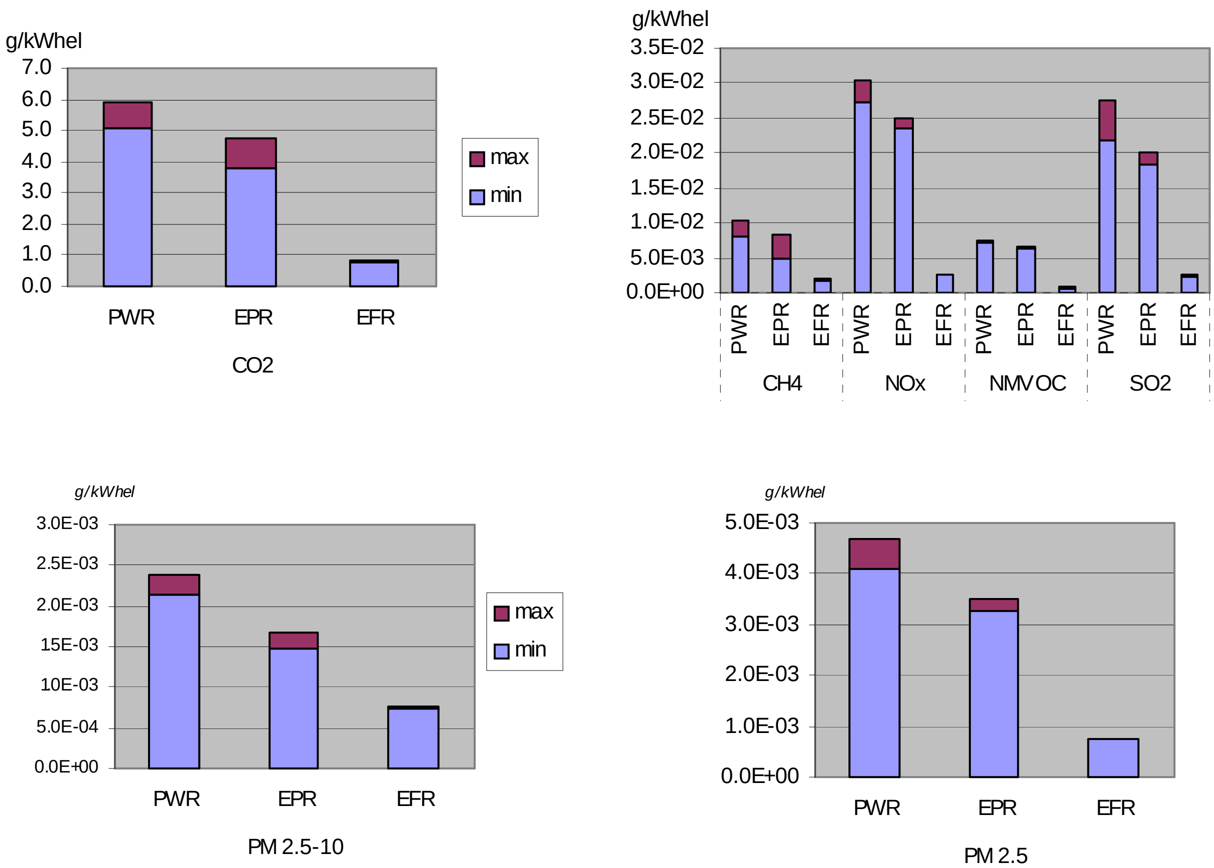

Figure 12 Ranges of non-radioactive emissions per kWh_{el} from different nuclear power plants
(minimum and maximum values for each technology correspond to the range of all considered scenarios but scenario 5 in different years, if applicable)

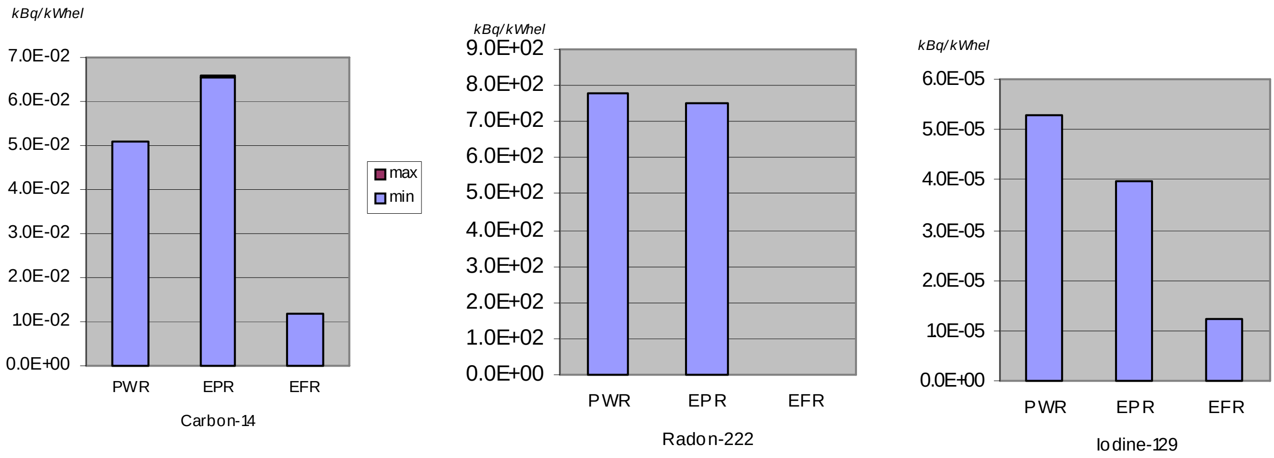

Figure 13 Ranges of radioactive emissions per kWh_{el} from different nuclear power plants
(minimum and maximum values for each technology correspond to the range of all considered scenarios but scenario 5 in different years, if applicable)

The figures 12 and 13 show the evolution of the emissions for each technology, with minimum and maximum values, for:

- time horizons 2000 and 2025 for PWR
- time horizons 2025 and 2050 for EPR
- time horizons 2050 for EFR

Except for C14 (see above), EPR results are lower than those of the PWR (for example, - 25 % for CO_2). The increase in C14 emissions from PWR to EPR can be explained by data constraints (the ecoinvent data for PWR do not provide C14 emissions into air).

EFR results are clearly lower than PWR and EPR results (for example, - 83 % for CO_2 from EPR to PWR), because emissions from the fuel step are marginal.

In general, the highest emissions for PWR are assessed to take place in 2000 whereas the lowest emissions are regularly obtained under the very optimistic scenario (VO 440 ppm) in 2025. Exceptions are the radionuclide emissions that are invariant between the different scenario-year combinations, and the land use is lowest for the current situation. The reason why land use increases will have to do with the assumptions underlying the different scenarios concerning the future power plant park in Europe.

For EPR, the lowest emissions are generally obtained for the two pessimistic scenarios either in 2025 or 2050 while the lowest emissions - as with the PWR - are regularly obtained under the very optimistic scenario (VO 440 ppm) in 2050. Again the radionuclide emissions are invariant between the different scenario-year combinations.

Very minor differences in the different EFR emissions result. This is because there are only two sets of data (i.e., only the realistic optimistic and very optimistic scenario in 2050) for which LCI data are available. It comes as no surprise that the emissions under very optimistic scenario are smaller than those for the realistic optimistic scenario which are only due to the emissions of the assumed UCTE mix.

5.3. Contribution analysis

In the following, a contribution analysis is presented that splits the key emissions into the four main life cycle phases, for each technology: PWR (base year 2000), EPR (base year 2025) and EFR (base year 2050).

2000: Pressurized Water Reactor (PWR), base year 2000

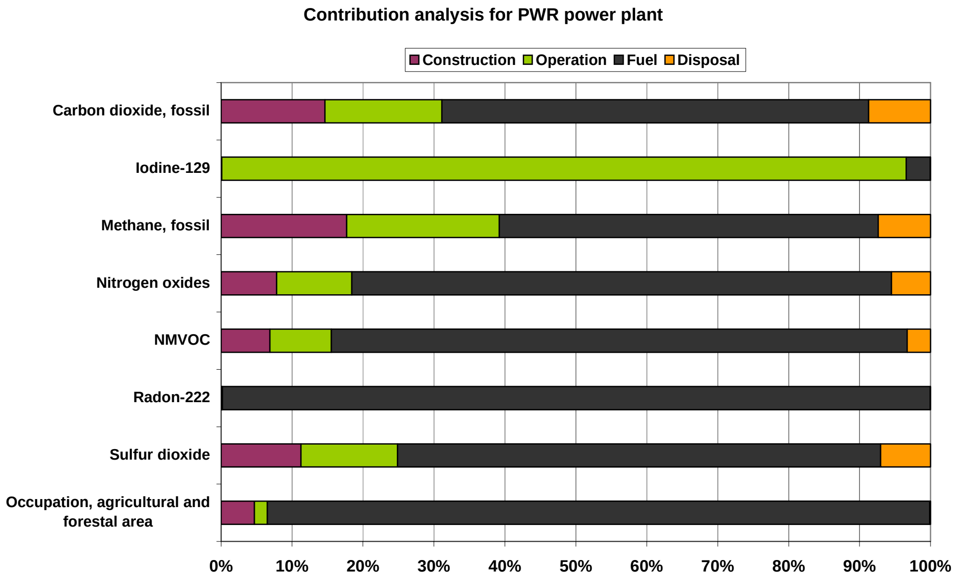

Figure 14 Contribution of the main life cycle phases to the emissions of key pollutants for PWR (current situation)

The results for the year 2000 reference technology highlight that the fuel step, including, among others, mining and enrichment, is the main step for a lot of the key pollutants, except for pollutants directly emitted by the nuclear power plant (such as Iodine-129, see Figure 14).

2025: European Pressurized Reactor (EPR), base year 2025

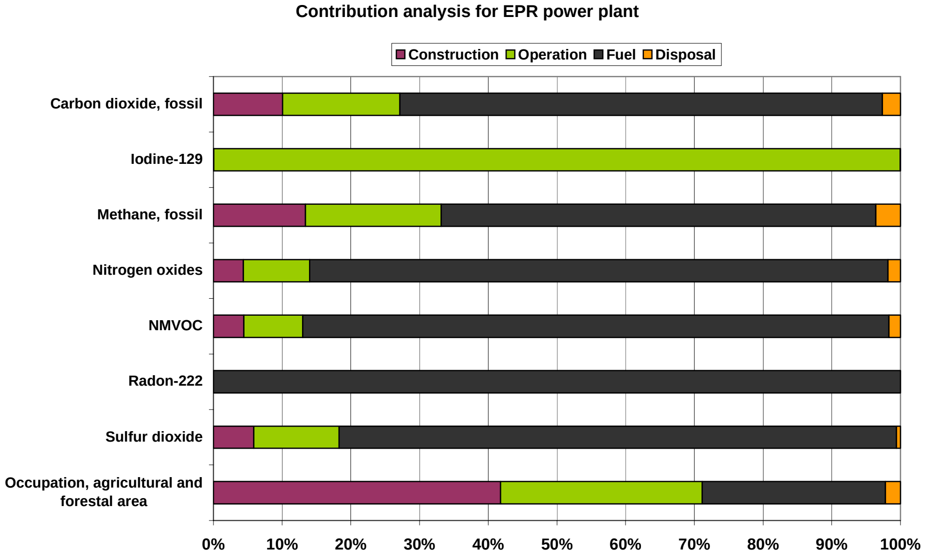

Figure 15 Contribution of the main life cycle phases to the emissions of key pollutants for EPR (base year 2025)

The results for the year 2025 reference technology show that the fuel step is the main step for key pollutants, except for pollutants directly emitted by nuclear power plant (such as Iodine-129; see **Figure 15**). The shares of contributions between the different life cycle steps for each pollutant are quite similar to the ones for the year 2000 technology.

2050: European Fast Reactor (EFR), base year 2050

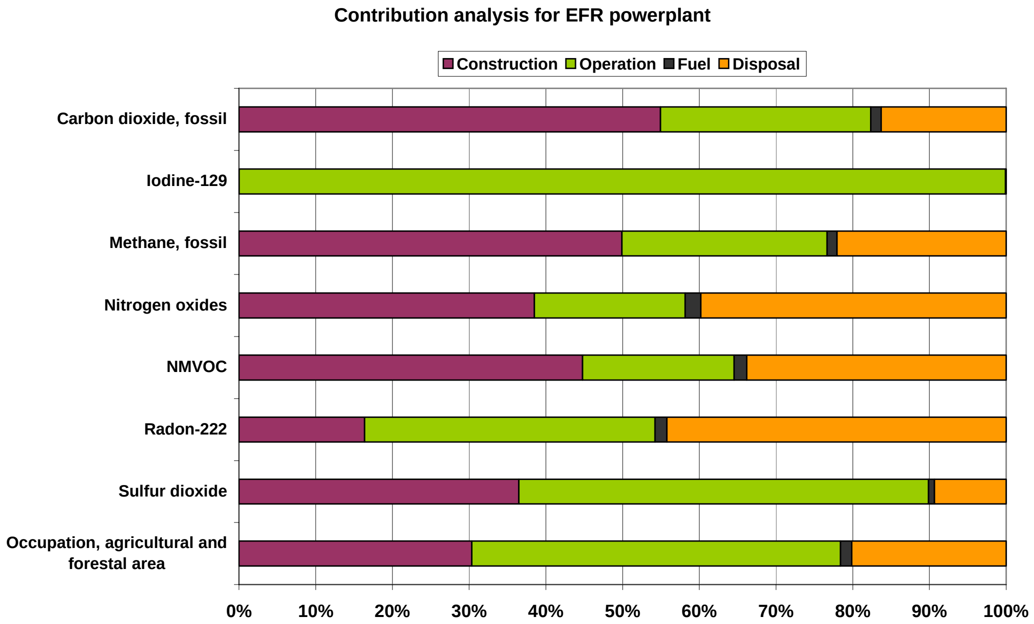

Figure 16 Contribution of the main life cycle phases to the emissions of key pollutants for EFR (2050)

Contrary to the previous two cases, the LCI results for the year 2050 reference technology reveal that the fuel step is a marginal contributor to the emissions of key pollutants (see Figure 16). This is because the fuel is by and large recycled so that activities related to mining, milling, conversion and enrichment are rather small. The emissions are therefore mostly caused by the three other steps (construction, operation and disposal), except for pollutants such as Iodine-129. The latter is explainable by the fact that our datas shows EFR does not emit Iodine-129. Given that EFR contributes only marginally to the electricity mix in 2050, however, all of the Iodine-129 in the LCI stems from non-EFR nuclear power plants in operation then.

6. APPENDICES

6.1.1. Conversion table used in the core report

1 FF (year 1997) = 1.029 FF(year 2000) = 0.15687 € (year 2000)

1 € (year 2001) = 0.984€ (year 2000)

extracted from INSEE statistics.

1 $ (year 2003) = 0.87 € (year 2003) = 0.87 X 0.9455 = 0.823 € (year 2000)

6.1.2. Evolution of uranium spot prices

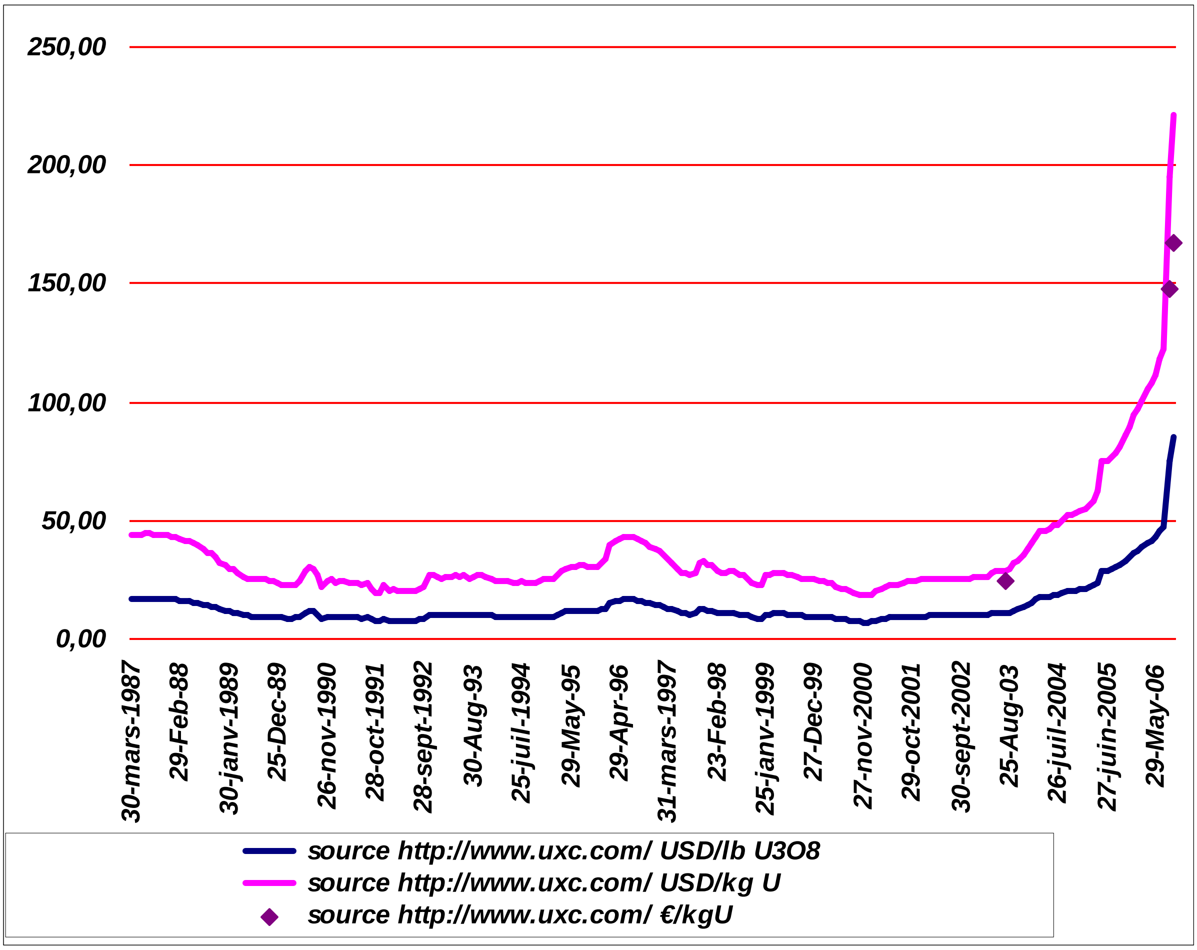

Table 17: evolution of Uranium spot price 1987-2007

6.1.3. Costs for future NPPs: a literature review by PSI

This paragraph is a literature survey conducted by the PSI in 2005. The editor does not endorse responsibility on its contents.

A comparison of costs of present nuclear power with advanced technologies is difficult, although several studies have attempted to make figures consistent (Tolley & Jones 2004; MIT 2003, Kröger & Fischer 1998). For future plants, total generation costs are calculated over the entire lifetime, while operating plants give costs which are amortized and whose composition and calculation may differ by operator.

For Generation III/III+ the estimation of costs is based on detailed calculations, actual orders (EPR, Finland), or in the best case on already operational units (ABWR, Japan). In the latter case, large part of the higher costs is explained by the expenditures for earthquake protection. Data available for Generation IV technologies are mostly goal values or first rough estimation, which would allow nuclear to be competitive (GIF 2002). Table 18 shows an overview of the available studies.

Table 18: Comparisons of current and future generation costs[51] (after Hardegger & Foskolos 2005; Hirschberg et al. 2005)

Cost [€/MWh]	Today	Future, a few decades from now	Source/Remarks
CH	26-34		Interval for current Swiss plants
	39	34	(Prognos 1999)
Germany Konvoi Type	29	15	(UIC 2004) (15 after full amortization)
OECD	29	21-28	(UIC 2004; OECD/IEA 1992)
Japan	58	48	ABWR (First unit), (UIC 2004; OECD/IEA 1998)
France	32	27	(UIC 2004; OECD/IEA 1998)
UK	34	-	(RAE 2004; UIC 2004; OECD/IEA 1998)
USA Production	14	-	(NEI 2004), amortized
USA DOE (55% Capital)	32	28	(NEI 2004; UIC 2004)
USA New Plants FOAK	-	39-58	First of a Kind costs (Tolley & Jones 2004)
USA New Plants Series	-	26-39	Cost Series (Tolley & Jones 2004)
EPR Finland (Today: BWR)	18	24	(Tarjanne & Loustarinen 2002)
EPR France	-	23-30	(DGEMP 2003)
EPR CH	-	26-34	Higher costs for waste disposal
GEN IV	-	16-23	(GIF 2002)

The costs of Generation III technologies are displayed in the Table 19 thereafter. For Generation III/III+ technologies, rather different values can be found. One must be very careful that the values known for recent investments are market prices and not costs. Differences between the first installation of a kind, as for the Finnish EPR under construction, and serial installations can be easily explained. For the latter, construction costs decrease by approximate 20 %, which reflects in a reduction of 5 % to 10 % of the total generation costs, depending on their cost structure. With

[51] According to PSI, this report is a literature survey, thus all the numbers are derived from sources, in these sources the given basic data such as € reference year, COD, discount rate may vary. PSI used as similar values as possible and stated special values as e.g. the full amortisation of the US-plants. Generally spoken: For today's values reported numbers are used, for future plants calculations or estimations were taken from the stated reports. The given values can be found in these reports.

estimated medium-term generation costs in the range of (for France) 23-26 €/MWh, EPR has chance to have lower costs than Generation II (on average 29 €/MWh). In the case of Switzerland, higher waste disposal costs will somewhat increase the total generation costs of EPR to 26 - 34 €/MWh, assuming different discount rates, as shown in Table 19 and Table 20.

Table 19: Comparison of costs for EPR Finland (First installation), France (Serial) and Switzerland (Serial) (Hardegger & Foskolos 2005; Hirschberg et al. 2005)

EPR		Finland (First) [a]	France (Serial) [b]		Switzerland (Serial) [c]	
Capacity	MW_e	1600	1600		1600	
Lifetime	a	40	60		60	
Discount rate	%	5	5	8	5	8
Construction cost (incl. interests)	M€	3.0	2.4	2.7	2.4	2.7
Specific Construction cost [d]	€/kW_e	1900	1500	1700	1500	1700
Capital cost	€/MWh	14	13	17	13	17
Operation cost	€/MWh	07	05	07	05	07
Fuel Cost (incl. Waste depository)	€/MWh	03	05	06	08	10
Generation Cost total	€/MWh	24	23	30	26	34

[a] (Tarjanne & Loustarinen 2002; Framatome 2003)
[b] R&D and external costs for emissions not included (DGEMP 2003)
[c] Investment and Operation cost as for France; Fuel cost are equivalent to those for current major Swiss nuclear power plants of the 1000 MW class Gösgen and Leibstadt; (KKG 2002; KKL 2002).
[d] Rounded.

Although the Finnish plant will be the first EPR ever built, the estimated costs are relatively low. This can be explained with four elements: a) the offer for the turn-key plant was relatively inexpensive; b) the Finnish government is securing favourable financial conditions; c) fuel costs are very low, which most probably is due to very low costs for on-site waste disposal; and, d) already signed long-term contracts with the paper industry. Construction costs will decrease for the serial French units[52] but, due to the somewhat higher discount rates[53], the final capital costs will be practically comparable with the Finnish case. French operation costs will be similar, while fuel costs will be somewhat higher than the Finnish ones. In Switzerland, capital and operation costs can be assumed similar to France, but fuel costs should be higher for the higher waste disposal costs, as for the presently installed Generation II units. The total generation costs are thus estimated at 26-32 €/MWh (Hardegger & Foskolos 2005; Hirschberg et al. 2005).

For Generation IV only goal values have been given to date. Compared to today's technology, reductions of 20-30 % for construction and 10-20 % for operation are aimed at. For constant fuel prices, total generation costs should be in the range 16 €/MWh to 23 €/MWh. Compared to Generation III/III+ generation costs, Generation IV should reduce them from 0 % to almost 30 % (see Table 20) (Hardegger & Foskolos 2005; Hirschberg et al. 2005). [54]

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[52] *Editor's comment: the official figures recently released in France regarding the EPR Flamanville 3 are the following: Generation cost is 46 €/MWh with a reference year for the currency that is € 2005. These figures are substantially higher than the older ones in the literature review. [EDF 2006]*

[53] *DGEMP calculates with 5-8 % of discount rate, while the effective rate for Finland is 2.6 %*

[54] *Editor's comment: these goal values for Generation IV production costs are very optimistic. Knowing the experience of the sodium FBR, it will already be hard to be just as competitive as the Generation III reactors.*

Production Costs GEN III/III+ (Offer values)	EPR Finland	24 €/MWh	Offer/Order Finland
	EPR Serial	19-23 €/MWh	Estimation Serial production
	EPR Serial France	23-30 €/MWh	Estimation for France
	EPR CH	26-34 €/MWh	For higher waste disposal costs
Production Costs GEN IV (Goal values)	Production w/o Capital	11-13 €/MWh	(10-20% reduction)
	Construction Costs	850-1700 €/kW$_e$	(20-30% reduction; rounded values)
	Production Costs total	16-23 €/MWh	Goal values

Table 20: Overview on Production costs for GEN III/III+ (EPR Order/Estimation) und GEN IV (Goal values) (Hardegger & Foskolos 2005; Hirschberg et al. 2005)

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