THE COMPETITIVE POSITION OF A GENERATION IV NUCLEAR POWER PLANT

An exploratory study for the Netherlands

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Contents

1 Introduction

Natural gas is the most important and abundant natural resource in the Netherlands and accounts for one fifth of the European gas extraction. The Dutch have the highest natural gas consumption rate in Europe and besides, the Dutch are net exporter. The Netherlands cover more than 75% of their own energy needs compared to 60% on average in the rest of Europe, mostly due to natural gas.

Natural gas is the primary fuel used for electricity generation in the Netherlands. Due to low capital investments and operational costs and a short time to market, gas - but also coal - fired power plants keep their share of energy supply. According to the Dutch Transmission System Operator, the Dutch electricity production capacity doubles by 2016 if all the present plans continue. With that, there exists even another 13.000 MW of production schemes that are on pending at the moment. The Dutch energy grid is expanding fast and the Netherlands became an exporting country since 2009. The following consequences are that the Dutch energy producers will position themselves more internationally so competition with foreign producers will increase. The public will enjoy the benefits of stable prices and certainty of delivery for the following generations. The energy market from an international perspective with growing cross-border delivery is a major business opportunity.

However, it is concerning that - business opportunity or not - natural gas is not an exhaustless resource and will run out over the next decades. Therewith, the negative environmental impact of energy production, transformation, handling and consumption becomes increasingly significant. Bearing these developments in mind, the future of the Dutch energy provision system will be under pressure. Therefore, it really needs thorough reconsiderations and at the time, there are only a few realistic options for securing national electricity generation:

- Increase efficiency in electricity generation and use;
- Expand use of renewable energy sources such as wind, solar, biomass, and geothermal;
- Capture carbon dioxide emissions at fossil-fuelled (especially coal) electric generating plants and permanently disposal of the carbon; and
- Increase use of nuclear power.

1.1 Problem statement

Restructuring the Dutch energy systems in the coming decades will increase pressure on social, technological, environmental, political and economic resources. Within this transition, the government is well underway in the exploration of new ways that fulfil their needs but the options, strategies and frameworks become increasingly complicated and the government has not yet succeeded in satisfying their ambition and meeting its objectives.

When considering the nuclear option above, it is necessary that our understandings must be revised compared to the first nuclear era, for continuing nuclear energy usage in the future. At this point, there is no clear perception of the potential of revolutionary nuclear reactor systems – that satisfy the sustainable requirements – due to the lack of satisfactory demonstrated practical experience and urgency. Therefore, the trend has been to continue the utilization of typical light water reactors (LWRs). Moreover, the market entrance of newly developed nuclear power plant (NPP) is generally a matter of financial profitability and capital risks.

1.2 Relevance

There is a rise in today's energy transition of new developed systems that seek smart ways for generating, extracting, saving and sharing energy on small scale, as yet no adequate technology exists to provide sustainable energy on large national scale. Evidently, these systems come with their own merits and demerits. To list a few, most of these systems are very sensitive to influences of one or more external factors such as: weather, peak & off-peak hours (Dutch: piek- en daluren), seasons, interchangeability between owners, temporary (battery) storage, subsidies, grid compatibility or are exclusively reserved to certain locations (e.g. hydropower). With most of these new energy supply systems under development and not 'yet' applicable in the least to large scale or for grid distribution, the importance of current established power plants remains.

Furthermore, to meet the future's needs for more secure, economical, efficient and inexhaustible energy delivery, nuclear energy systems will have to be reconsidered. The principles of a sustainable nuclear energy system concern the conservation of resources, protection of the environment, preservation of the ability of future generations to meet their own needs, and the avoidance of placing unjustified burdens upon them. Therefore, the goals for future nuclear energy systems imply the needs for improved waste management, a minimum of environmental impacts, effective fuel utilization and the development of new energy products that can expand nuclear energy's benefit beyond electrical generation (GIF, 2002).
For this research effort, the Lead-cooled Fast Reactor (LFR) was considered because it has some characteristics that are favourable over other prospective nuclear power plants. This will be explained in chapter 3.

1.3 Stakeholders

The challenge is to position a prospective NPP in a deregulated market in which utility exploiters make the investment decisions as the government only formulates a basic set of conditions. The market is further ruled by innovative market entering systems, current established power plants, the need for energy products other than electricity, market internationalization, the ease of the import & export of energy products and cross border electricity grids.
The aforementioned will likely determine the economic viability in the future but also the competitive advantages and disadvantages to other technologies.
To simplify the problem, the stakeholders are facing two options: (1) a proven technology that is known to be viable and (2) a prospective technology that offers superior performance results but whose viability is not a fully certain outcome.

1.4 Goals

The aim of this research is to tell if a more sustainable nuclear reactor can be part of our future energy mix. In other words, the aim is to disclose if the LFR (1) can offer a sustainable solution to future energy challenges and (2) is a competitive option on tomorrow's energy market.

The aim as explained above is dependent on the LFR‘s competitive economics and operational performance. Therefore, this research is set forth in the following goals:

- The first goal is to provide a clear understanding on today's energy needs, energy policy and energy provision in relation to our society. This will give the reader a sound basis for understanding the relevance of this research.
- The second goal is to show the competences and goals of revolutionary nuclear reactor designs and their relevant social and technological challenges. Additionally, the choice for the particular LFR design will be explained.
- The third goal is to provide insight in the costs structure of this particular LFR system so it can be compared with the market supply systems.
- The fourth goal is to present a projection of the future energy market system. The future is represented by four plausible scenarios that are based on the most critical uncertainties regarding new nuclear energy deployment.
- The final goal is to deliver a tool by which mutual NPP performance can be measured. The purpose of this tool is to assess the advantages and disadvantages of the LFR's performance compared to a current established NPP. For this assessment, the stakeholders' preferences are also taken into consideration, since they decide what is important.

1.5 Research question

To provide profound knowledge in the competitive position of the LFR, the following main research question is asked:

Can the LFR be more advantageous than current market alternatives in terms of economics and performance?

Seen the extensiveness of this question, it is divided into the following sub-questions:

- Does the LFR have practical benefits for the future's energy mix;
- Does the LFR have economic advantages in terms of electrical energy production costs and capital risks over the alternatives;
- What is the supply and demand cost structure of the electricity market, and how will this likely evolve;
- How does the LFR perform compared to existing NPPs;
- What do stakeholders prefer regarding NPP performance;
- How can the LFR be deployed in the future, regarding which product-market combination;

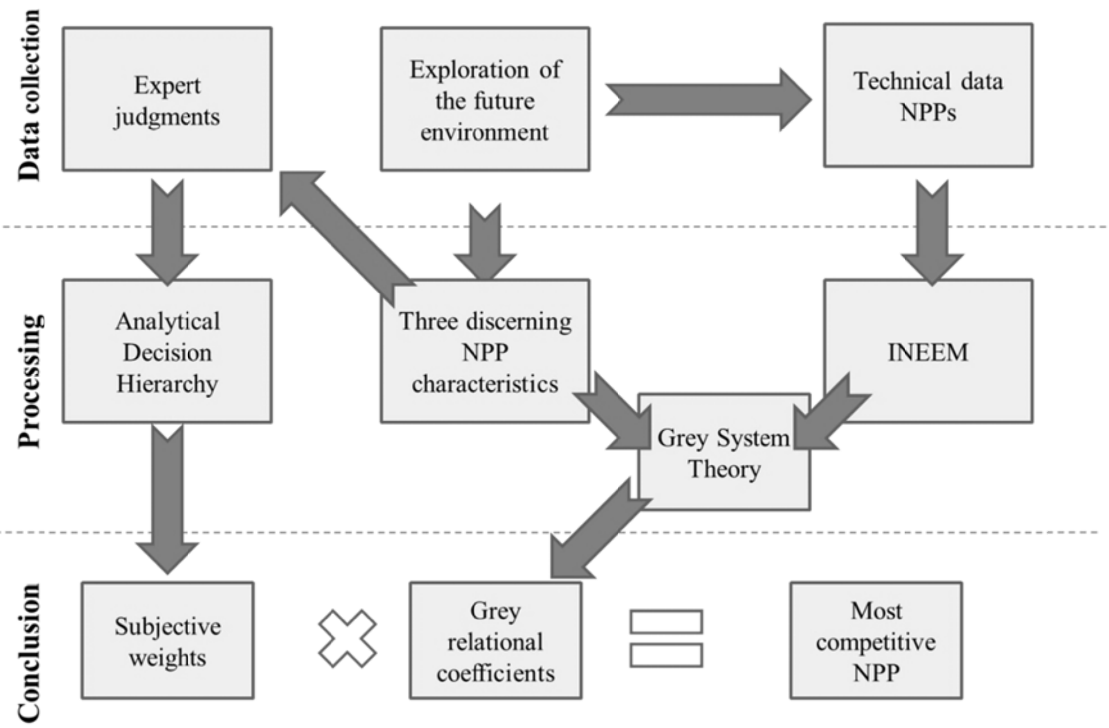
1.6 Research design and boundaries

The research is composed from three different but closely related studies (see figure 1.1). The elaborated results will be integrated into the final conclusion and recommendations. The LFR stands central throughout these studies.

First, the total cost estimate will be performed by using the Integrated Nuclear Energy Economics Model (INEEM). Based on technical data of the a LFR system's design, all

nuclear power plant lifecycle costs are calculated and put together to assess capital at risk and the levelized unit of electricity production cost.
Second, the future market will be investigated by desk research. Scenario planning methodology will be used to determine how this future market will evolve, with the focus on uncertainties. These uncertainties will point out what the external factors are that influence the cost competitiveness.
Third, a Multi Attribute Decision Making (MADM) tool will be designed that is capable of incorporating the systems' performance figures as well as stakeholders' preferences. This tool consists of the Grey System Theory and Analytical Decision Hierarchy. The competitiveness of the LFR in relation to an established NPP will then be assessed with the use of this tool. The results from the three models will first be analysed separately and then elaborated into the final conclusion. This conclusion shows what the competitiveness of the LFR system is.

Figure 1.1: Research design



1.7 Expected results

The expected results of the scenarios, INEEM and MADM for the particular LFR are a clear understanding of:

- Competitive advantages/disadvantages in comparison to that of other NPP;
- Future electricity product demand and supply developments;
- The window of opportunity given that:
  Delivery certainty in high quantities against low emissions compared to other technologies.
- A decision support tool to measure relative performance.

The results are processed into an advice to the above mentioned stakeholders so they can assess whether or not the LFR can be accepted in their business case portfolios.

1.8 Reading guide

Chapter 1
First, the general introduction, relevance and design for this research are explained. At the end of this chapter, a list of used abbreviations is given.

Chapter 2
This chapter provides the basics of the current energy demand, provision and policy of the Netherlands. It starts with a description on today's developed society, followed by a reflection on the Netherlands. Then, the Dutch energy provision system is briefly described accompanied with a description of the Dutch energy policy.

Chapter 3
The development objectives of next generation nuclear power plants are explained, followed by a brief explanation of the physics within a reactor. Then, the fuel cycle differences are explained with their advantages and disadvantages and the choice for the LFR system will be pointed out. The chapter finalizes with a review on the Dutch nuclear energy program and the Dutch public debate.

Chapter 4
After the basics of nuclear power, the detailed costs structure and economics of the LFR are given. All life cycle cost formulas and the derivation of these formulas of are stated. The chapter is finalized with the results in comparison to a current established reactor.

Chapter 5
This chapter briefly explains the scenario background, followed by the procedure of drafting scenarios. Then the environment of the LFR is described and the near term and future costs of electricity production are given. Finally four plausible scenarios for NPP deployment in the Netherlands are drafted. These scenarios provided 3 distinctive NPPs that will be compared in chapter 6. Based on these scenarios, a conclusion is derived.

Chapter 6
In this chapter, the elaboration of the MADM tool is shown and the two methods that are introduced, the GRA and AHP will be explained. All necessary steps that were made regarding the GRA and AHP methods are stated. The results are explained showing which of the three NPPs performs best. Based on this relative performance measurement, a conclusion is derived.

Chapter 7
This is the final chapter of this research. It finalizes this research with the general conclusion of this research and answers the research questions. It is followed by the discussion that states some notes to how this research is performed and what might be necessary to do in the future. The chapter finalizes with recommendations based on the outcome of this research.

1.9 List of abbreviations

°C	= Degree Celsius
€/MWh	= Euro per Megawatt-hour
BWR	= Boiling Water Reactor
CO_2	= Carbon Dioxide
DH	= District Heating
EPR	= European Pressurized water Reactor
FR	= Fast Reactor
Gen	= Generation
GWe	= Gigawatt electric
GWh/yr	= Gigawatt-hour per year
HLW	= High-Level radioactive Waste
kgHM	= Kilogram of Heavy Metal
Km/s	= Kilometres per second
kW	= Kilowatt
kWe	= Kilowatt electric
kWh	= Kilowatt-hour
kWh/yr	= Kilowatt-hour per year
LILW	= Low- and Intermediate-Level radioactive Waste
LFR	= Lead-cooled Fast Reactor
LWR	= Light Water Reactor
MW	= Megawatt
MWe	= Megawatt electric
MWth	= Megawatt thermal
NPP	= Nuclear Power Plant
PWR	= Pressurized Water Reactor
TW	= Terawatt
TWh	= Terawatt-hour
US$	= United States Dollar

2 Context

In our world today energy became for granted. Its consumption has brought the world prosperity and made developments possible like wealth, health, comfort and technology advancements. Unfortunately also negative consequences exist like the exhaustion of fossil fuels and harmful impacts on the environment. Since these aspects of energy, prosperity, fossil fuels and environment are so strongly interrelated; a nation's governmental energy policy became obviously important. In order to underpin these statements, this chapter gives a closer review on the Dutch circumstances.
First, a description on today's developed society is given, followed by a reflection on the Netherlands. Then, the Dutch energy provision system is briefly described accompanied with a description of the Dutch energy policy. Finally the market is described and the chapter closes with a conclusion.

2.1 Energy demand and human development

The relation between society, prosperity, energy consumption and environment is demonstrated by several sources e.g. United Nations Department of Economic and Social Affairs (UN/DESA) (2008), Statistics Netherlands (Dutch: CBS) (2007) and Massachusetts Institute of Technology (MIT) (2003).
According to the United Nations; in 2005 the world population reached 6.5 billion persons and is expected to reach 9.2 billion in 2050 (UN/DESA, 2007). This increase will occur mostly in new developing countries as a result of increasing affluence, whereas the population of developed regions is expected to remain nearly unchanged (at 1.2 billion). There are three important evidences that development of society is related the growth of electrical energy consumption, namely:

1. *Rapid urbanization*. According to the UN: 'In 1900, urban dwellers made up only 13% of the global population, whilst in 2005, the urban population reached 49% and the expectations are that by 2030, 60% (about 5.0 billion people) will live in urban areas'. Currently, the average grow rate in developed regions is 0.6%, whereas the grow rate in less developed countries is higher 2.7%. About half the world's population lives in urban areas and still, the urban settlements were estimated to occupy merely 2.7% of the world's land area. The International Energy Agency estimates in the World Energy Outlook (WEO) of 2008: cities emit around 71 per cent of global CO2 emissions – potentially rising to 76 per cent by 2030 (IEA, 2008).

2. *Economic development*. An essential and fundamental aspect of economic development is the increasing concentration of activity in high value added service and industry sectors. Where service sectors which are mostly concentrated within the urban areas the agricultural and industry sectors are more likely to be located outside or away from these urban areas. In most countries, the share of services has been rising in recent periods contrary to agriculture which has declined.

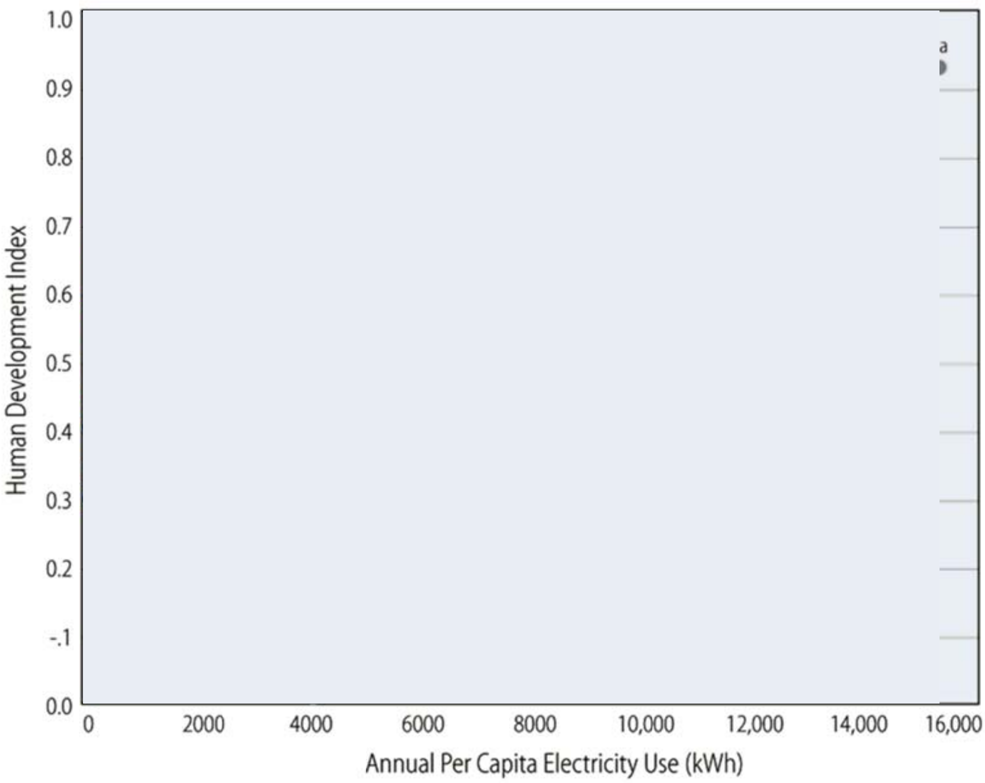
3. *Human development*. To develop and sustain urban life, access to energy is essential. The energy use per capita on average is five times greater in the more developed regions than in the least developed countries. Whereas energy consumption in developed countries has continued to increase and currently accounts for about 70% of the world energy demand, much of the future growth in energy demand is expected to

occur in developing countries where a large proportion of the population still lacks access to modern, high-quality energy sources.

The impact of CO2 emissions per person are remarkable higher in the more developed countries (11.9 metric tons per capita) than in the less developed countries (0.2 metric tons per capita) (UN/DESA,2008). A large contribution to these numbers is the ownership of passenger cars and the transportation of goods and services by road which again are associated with economic and industrial growth. Transportation now accounts for about a quarter of the world energy use and in addition, it consumes about half of the world's oil supply. The number of motor vehicles per capita in the less developed regions remains markedly lower than in the more developed regions, but is now increasing more rapidly than in the more developed regions.

Without doubt, there is some relation between developed and developing regions and their energy consumption. Nowadays, vast literature exists on the relationship between development and energy consumption (e.g. IEA, 2008; Statistics Netherlands, 2007; MIT, 2003; UN/DESA, 2008; Wolde-Rufael, 2010) although the causality seems bilateral i.e. there is no general conclusion when nations started using energy, prosperity follows or that a nation became prosperous which led to increased energy consumption (Wolde-Rufael, 2010). One thing that can be said is that there is a strong correlation between both. Figure 2.1 adapted from the MIT (2003) shows the mean energy usage in relation to the UN global Human Development Index (HDI).

Figure 2.1: The correlation between the Human Development Index and mean electricity consumption per capita.



The line dividing advanced and developing countries is adopted from the United Nations HDI and is 4,000 kWh per person per year.

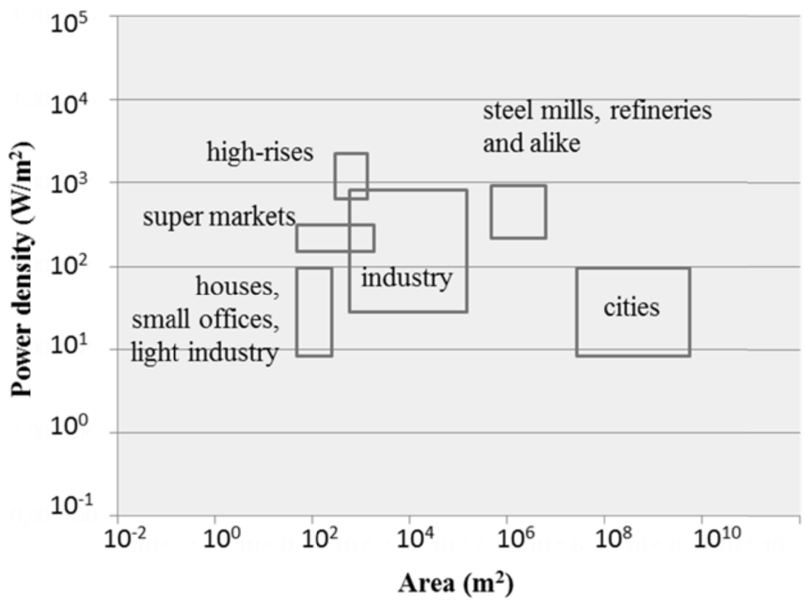
Source: Massachussets Institute of Technology, 2003 p.109

2.1.1 A high energy density society

To finalize these societal developments, it is necessary to place electrical energy in the context of urban development. The increasing population growth in urban areas with its ever growing demand for energy will complicate the way energy is provided and it affects the way energy is generated, transported and distributed and consumed.

Modern high-energy civilization develops commercial activities and industries with very high energy densities. These energy densities of modern society were investigated and quantified by Smill (2003) as projected in figure 2.2. The power densities for houses, low energy manufacturing and offices and cities as a whole typically range from 10-100 W/m^2. As for supermarkets and office buildings, a range of 200-400 W/m^2 applies. High rise buildings range up > 3 kW/m^2. Energy intensive industries are in the range of 300-900 W/m^2.

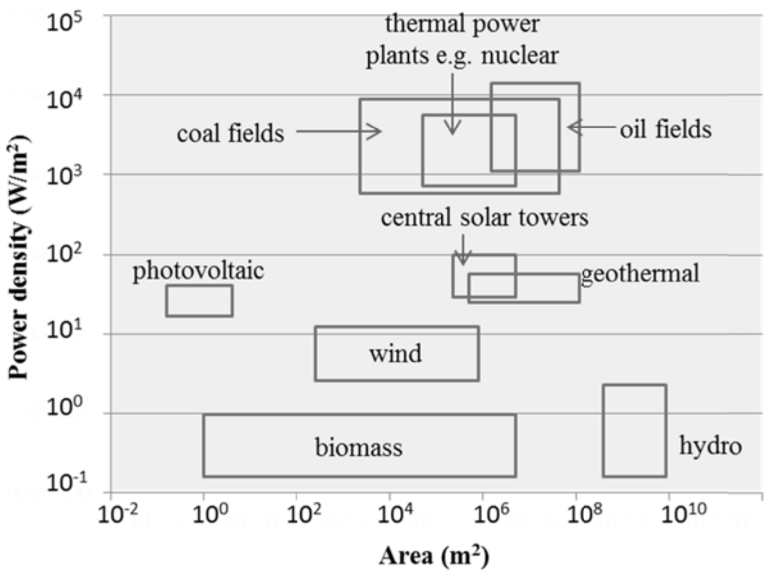
Figure 2.2: Typical power densities of today's society



Source: Smill, 2003 pp.242-243

For these intensities, power is mostly supplied by thermal electricity plants (i.e. steam driven turbines that are linked to a generator) and fossil fuels, as they range in densities of several of orders of magnitude larger than their consuming destinations as shown in figure 2.3.

Figure 2.3: Typical power densities of modern energy provision



Source: Smill, 2003 pp.242-243

The existing renewable energy sources are not capable of matching such densities as shown in figure 2.2. Current developed photovoltaic cells are capable of converting solar radiation into electricity in the range of 20-60 W/m^2, geothermal energy extraction ranges from 20-40 W/m^2, wind generates electricity in the range between 5-20 W/m^2, and biomass produces less than 1 W/m^2. Mankind therefore relied predominantly on fossil fuels. As for the moment; renewables can only provide a small proportion of final uses mostly applicable for heating and lighting energy efficient houses where electricity generation by photovoltaic cells is the best example.

2.1.2 The Dutch society

The Netherlands fit the profile of a highly developed, high energy consuming and densely populated nation as shown is in table 2.1. Between 2000 and 2006, the amount of people in the Netherlands in (very dense) urban areas increased with over half a million people (Statistics Netherlands, 2007). This tremendous growth is caused in the first place by the decrease of people in non-urban areas, but also in the second place by an increase in areas with urban characteristics. With 80% of its population now living in urban areas, the Netherlands is one of the countries where life centralized, densified and urbanized. On average, almost half of the population owns a motor vehicle and has an energy consumption rate just above west-European average. The Dutch confirm to the image of a high energy density society.

Table 2.1: The Dutch society and its urbanization, energy demand and environment

	The Netherlands	Western Europe[1]	World	
Total population (2005) *(x 1000)*	16 328	186 609	6 514 751	
Land area (2005) *(km²)*	33 880	1 088 182	192 830 789	
Urban settlements (2000) *(% of land area)*	36.6	16.6	2.7	
Number of urban dwellers (2005) *(x1 000)*	13 095	141 992	3 164 635	**Urban population**
As percentage of total population (2005)	80	76	49	
Average annual growth rate (2000 – 2005) *(percentage)*	1.4	0.5	2.1	
Density (2005) *(per km² of urban extent)*	1 056	788	902	
Percentage w/ access to improved sanitation (2004)	100	100	80	
Percentage w/ access to improved water source (2004)	100	100	95	
GPD per capita (2005)	34 289	31 572	9 462	
Value added by industry and services (2005)	98	99	92	
Energy use (2004) (*kg of oil equivalent per capita*)	5 051	4 453	1 713	
Carbon dioxide emissions (2004) *(metric tons per capita)*	8.7	8.3	4.5	
Motor vehicles in use (2000-2005) *(per 1 000 of population)*	495	544	153	

[1]: Western Europe: Austria, Belgium, France, Germany, Liechtenstein, Luxembourg, Monaco, Netherlands, Switzerland

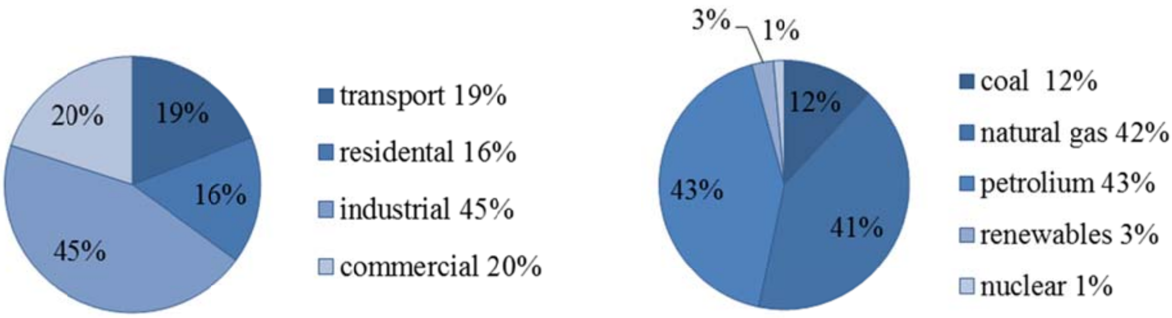
Source: United Nations Department of Economic and Social Affairs, 2008

2.2 The Dutch energy provision

After understanding that the Netherlands are an energy consuming society, it is important to understand the Dutch energy system and provision structure. As shown above, the Dutch economy is relatively energy intensive. This energy is mostly provided by fossil fuels as shown in figure 2.4.

The annual energy demand of the Netherlands was approximately 128 TWh in 2007 (ECN, 2007). Industry is the most energy consuming sector, mostly due to the large (petro) chemical industry and greenhouse farming. More than half of the industrial energy consumption concerns the use of energy commodities as raw materials for processing products like plastics from petroleum. Petroleum is only extracted in small amounts on Dutch soil and therefore it has the biggest share of imported energy commodities, followed by coal which was extracted in the Netherlands before it became uneconomical.

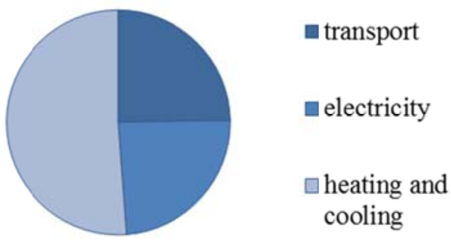
Figure 2.4: Distribution of energy consumption among different sectors (left). Dutch energy consumption to energy source (right)



Source: Statistics Netherlands, 2007 p.107

The Dutch know the highest natural gas consumption in Europe and natural gas is the primary fuel used for electricity generation in the Netherlands. A small amount of electricity is generated by the single currently operated nuclear power plant Borssele (approx. 485 MW) in the southwest of the Netherlands, which accounts for about 1.3% of the Dutch energy consumption.

Figure 2.5: The proportional relationship between of energy commodities for heating and cooling, transport and electricity.



Source: Ministry of Economic Affairs, Agriculture, and Innovation, 2011 p.21

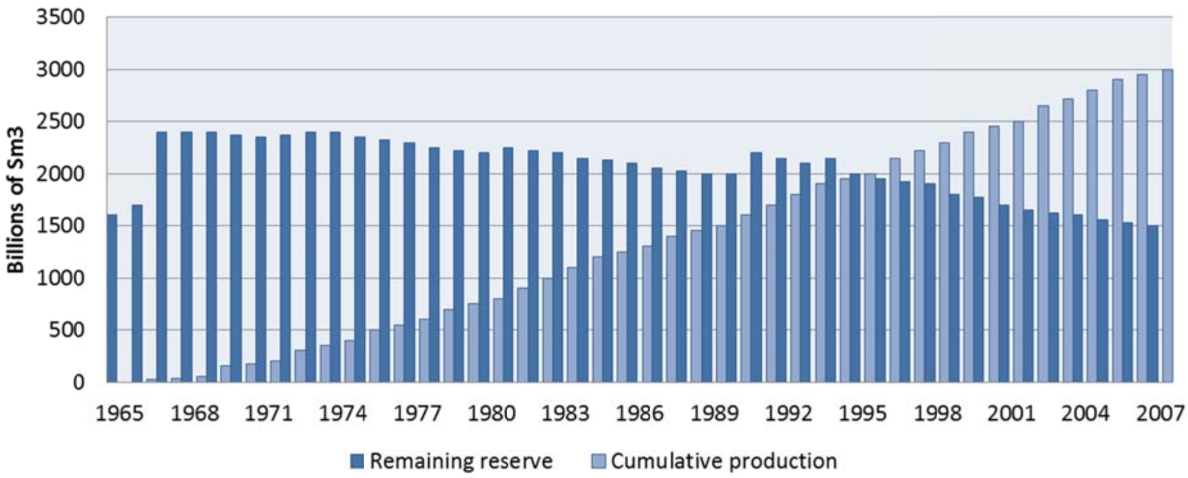
Besides generating electricity, natural gas is largely used for heating in both residential and industrial sectors as shown in figure 2.5 by the Ministry of Economic Affairs, Agriculture, and Innovation (EAA&I) wherein the industry, natural gas of course also finds other applications.

2.2.1 Natural gas and oil

Natural gas is the most important and abundant natural resource in the Netherlands and accounts for one fifth of the European gas extraction and the Dutch are net exporter. The Netherlands cover more than 75% of their own energy needs compared to 60% on average in the rest of Europe, also due to natural gas. In 2008, 58.8 billion m3 of natural gas was exported. This was the largest amount since the discovery of natural gas in Slochteren around 1990. The trade surplus in 2007 was almost 50% higher with respect to 2006, mostly caused strong price rises of natural gas lately. The trend of production and related reserves is shown in figure 2.6 and 2.7 for gas and oil respectively. Besides this trade surplus caused by overproduction, import has also risen as the Dutch resell gas to foreign countries. Gas profits significantly contribute to government revenue which in 2008 was about €8 billion, excluding corporate taxes (EA, 2008)

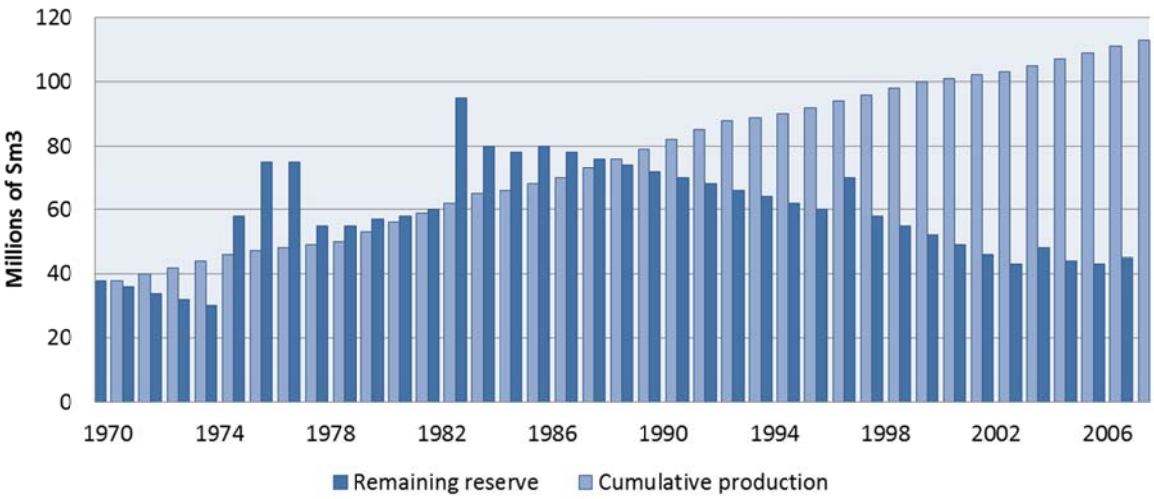
Partly thanks to its own production of oil and gas, the Netherlands have developed a strong oil and gas extraction industry. This industry is important for the country's own oil and gas extraction but also plays an important part internationally in the offshore oil and gas industry. The Dutch have a large amount of expertise in oil and gas extraction in areas that are difficult to access. The Dutch market potential present for this industry worldwide is estimated around € 17 to €35 billion (EA, 2008).

Figure 2.6: Dutch gas reserves and production.



Source: Ministry of Economic Affairs, 2008 p.40

Figure 2.7: Dutch oil reserves and production.



Source: Ministry of Economic Affairs, 2008 p.39

2.2.2 Electricity supply and demand structure

As mentioned above, the current electrical energy demand of the Netherlands is about 128 TWh. For the short-term, ECN took the growing energy demand from the Global Economy Scenario of the IEA and projected it on the Netherlands what came down to roughly 140 TWh under current circumstances for the year 2020 (ECN, 2010a). This rising demand is based on population growth, GDP and technology advancements and the aimed energy usage efficiency will hardly slow down the demand.
Therewith, in a liberalized free market it is likely that, in the long term, increased consumer efficiency will do little or nothing to improve the reserve capacity margin or the reliability of network infrastructures. This can be explained as follows: ‘For assured security of supply one needs, first, to minimize the risk that power companies temporarily withdraw electricity supply from their customers and, second, to improve the capacity of power companies to rectify rapidly technical faults with the electricity transmission and distribution infrastructure’. (Nutall, 2004)
Nutall further states that: ‘Electricity companies are regulated with regard to the quality (voltage, frequency smoothness etc.) of the electricity they supply. There is therefore little scope to adjust the amount (voltage) of electricity supplied to consumers when supply and demand is out of balance’. Thus, a serious shortage of supply with respect to demand can cause unacceptably low supply voltages (brownouts) or even force grid operators to disconnect consumers from the system (blackouts).

For the Netherlands goes that there needs to be approximately 15% of surplus generation to prevent power blackouts due to insufficient generation, possible technical failures and to perform maintenance to guarantee delivery certainty (TenneT, 2010). For technical reasons, some types of generation such as nuclear power are largely unable to operate in such a load-following or supply and demand mode and hence are best left to run at a continuous level irrespective of consumer demand. This type of operation is termed ‘base load’.

2.2.3 The expansion of the Dutch electrical energy market

The General Energy Council (GEC) mentions that ‘*from recent market activities it seems that the Netherlands have become an interesting place of business regarding energy generation*’ (GEC, 2009). They point out that a reason for this could be increasingly harsh regulations for thermal surface water pollution in rivers (like in Germany and Austria) which make the establishment of (new) power stations more difficult whilst in the Netherlands seawater can be used for cooling (mostly for nuclear and coal-fired stations). The Netherlands also have the advantage of deep sea docks to convey fuel (coal-fired stations) and to provide offshore wind farms. Not to mention the Dutch role in import, export, transit, storage and trade of gas.

This competitive advantage that the GEC summarizes above is also acknowledged by the Ministry of EA, who mentioned the Netherlands in this perspective as a ‘*powerhouse*’ that will exploit its competitive advantage further by exporting energy to e.g. Germany (EA, 2008). As ordered by the GEC and the EA, TenneT executes the plans to adjust and improve the grid to make this export possible (TenneT, 2010).
Also the Energy research Centre of the Netherlands (ECN) (2007) endorses the fact that not only competition increases, but also the size of the market that can be supplied with electricity from Dutch power plants, due to the expansion of the number of interconnections and increased integration with electricity markets in neighbouring countries. In investment decisions, electricity producers will be able to choose from various national electricity markets.

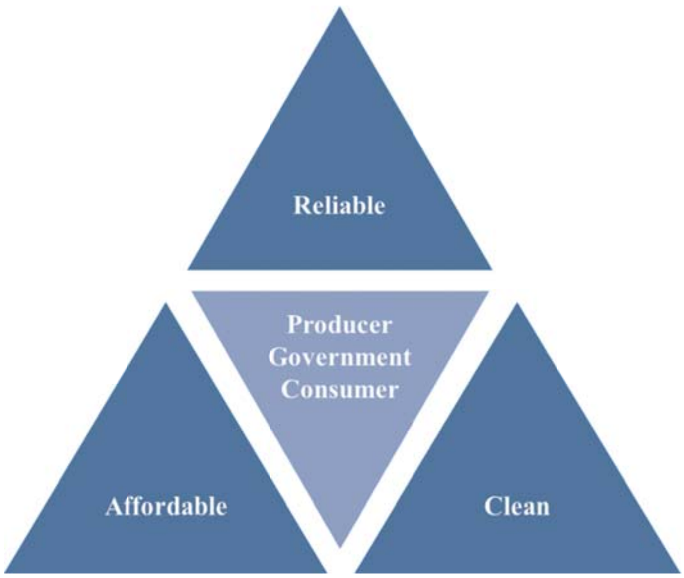
The export of energy comes not only from a business opportunity point of view, but also as a consequence from the current energy policy on sustainable energy sources. It is concluded that primarily in 'off-peak hours' (Dutch: Daluren) where there is more supply than demand, the surplus energy - especially due to high penetration on the grid that is produced by wind farms - must be channelled to foreign countries (GEC, 2009; ECN, 2010a).

Regarding nuclear energy, ECN further stated that: 'given the expected returns on investment in a base load power plant, the Netherlands seems an attractive market. Other aspects that are taken into account by the electricity producers are; the national legislation and regulations for nuclear energy, the existence of reservations in the spatial planning for the construction of nuclear power plants, the availability of cooling water and options for connection to the electricity transmission network.*'* (ECN, 2007)

2.3 The Dutch energy policy

To acknowledge the strategic position of the Netherlands within Europe and to allow the Dutch enter the global energy market, the government endeavours after a policy that offers the utility exploiters the opportunity to expand. The Dutch energy sector is liberalized, so the government only sets goals, motivates, stimulates and directs the change of our energy systems, whereas the market parties make investments to provide the energy mix. Internationalization makes the energy mix defined by international market parties which puts more pressure on the government to set the basic conditions and ensure its own interests.
The three main interests for the government's energy policy are: reliable, affordable and clean (figure 2.8). Below the figure the three interests are briefly explained.

Figure 2.8: Public energy interests



Source: Ministry of Economic Affairs, 2008 p.14

Reliable:

- Security of supply: by means of long-term available energy sources. This relates production capacity to known global energy resources, their distribution and consumption;
- Security of delivery: the degree in which consumers can rely on delivery;
- Crisis resistance: if national and international energy crisis may occur, can the national energy supply manage the consequences.

Affordable:

- Economic efficiency: static efficiency achievement by lowest possible margin costs as well as long term dynamic efficiency by using the best possible mix of energy sources.
- Competitive power: particular business related interest meaning that the government puts up a well regulated and attractive place of business to compete internationally.
- Purchasing power: simply put, energy must remain affordable for both business and consumer.

Clean:

- Greenhouse gas emissions: emissions of greenhouse gasses, especially carbon dioxide must be kept as low as possible through the entire chain.
- Other waste materials: waste materials like the gasses NO_X and SO_2, particulate manner and others like nuclear waste must be limited as much as possible.
- Other environmental aspects: all sorts of harm to the environment in losses of biodiversity, forestry, preservation areas and other landscape aspects must be limited.

2.3.1 Optimal use of natural resources

In the coming decades, our own gas and oil stocks will decline as projected in figures 2.6 and 2.7 and imports will increase consequentially. Therefore it is very important for the Netherlands that these energy sources will be used optimally. High energy prices mean that the state treasury will see large amounts of funds in the form of natural gas and oil profits, but over the slightly longer term, the stream will dry up due to decreasing production. So the government will become ever more charged with allocating the fossil and financial resources so that future generations will also be able to benefit from the Dutch natural gas assets.

2.3.2 Additional objectives

Regarding global warming concerns, the Dutch said that the Kyoto targets will not be sufficient to prevent dangerous global climate change according to the Dutch Ministry of Housing, Spatial Planning and the Environment (HSPE) (2010). Therefore the Dutch government has formulated ambitious new climate and energy targets for 2020 in order to become one of the cleanest and most energy efficient countries in the world.

These targets are:

- to cut emissions of greenhouse gases by 30 % in 2020 compared to 1990 levels;
- to double the rate of annual energy efficiency improvement from 1 to 2 % in the coming years;
- to reach a share of renewable energy of 20 % by 2020

With these ambitions the Dutch government follows the 2007 European spring Council which concluded that a reduction of greenhouse gas emissions of 30 % by industrialized countries by 2020 is necessary to limit global climate change to 2 degrees Celsius above pre-industrial levels (HSPE, 2010).
The Dutch are underway to meet the Kyoto target of 6 % reduction of greenhouse gas emissions by 2012. According to the GEC however, the climate objectives the Dutch have set themselves will not be achieved (GEC, 2008). This is also confirmed by a report from 2009 performed by the Netherlands Environmental Assessment Agency (NEAA) as ordered by the ministry of HSPE. According to this report: 'aims for the medium and long period regarding GHG reduction as set in our national policy as well as the aims set by EU policy, will not be achieved with the current efforts that have been made so far.' (NEAA, 2009)

With other EU member states not able to achieve such ambitions as well, the Netherlands and the EU have revised their goals to 14% renewable energy by 2020. The recently updated energy policy of Ministry of Economic Affairs, Agriculture, and Innovation (EAA&I) also tells us that the objectives to cut GHG to 30% related to the levels in 1990 are set back to a mere 16% (EAA&I, 2011).

2.3.3 Updated energy strategies

The above mentioned stagnations of the energy transition policy are set forth in an advisory report of the Council of Spatial, Environmental, and Natural sciences (CSEN) (2010), stating that it is caused by: 'a lacking of sense of urgency, the lacking of a long-term strategy where 2020 is preferred to be replaced with visions up to 2050, systematic avoidance of political choices and a lack of structure.'
Therefore the government has adapted more realistic and business like strategies according to its recently updated energy policy (EAA&I, 2011). It set forth its policy with five main spearheads, namely;

- *A modern industry policy*: The Netherlands dispose of a strong innovative energy sector. The government wants to strengthen this sector and qualified it as an economic top sector. It concerns both green and grey energy, where the policy focuses on the strategic position of the Netherlands as a gas-country and where innovation in renewables is necessary to make it affordable and competitive.

- *Expand the share of renewables*: renewables are essential for the future energy provision. It is clear that costs go before the profits however the policy is that is must be achieved as economically as possible. This directs that almost affordable sources techniques will be exploited first with emphasis on innovation of other techniques.

- *Offer room for all energy options to 2050*: the government is striving for a well-balanced energy mix between all sorts of green and grey. The Netherlands should profit from its competitive advantages which will lead to a cheap as possible mix. The government acknowledges that fossil fuels cannot be abandoned yet – so emissions of CO2 gasses will not be fully excluded, but it tries to mitigate it by; the emission trading system (ETS), carbon capture and storage (CCS), renewables and nuclear power. For the latter, the government stated that nuclear power is strictly necessary to achieve a low CO2 economy, more import independence and delivery certainty.

- *Green Deal*: a sustainable society cannot be achieved by government policies and subsidiary programs alone. A sustainable society therefore demands a joint trajectory where society and government strive for the same ambitions. Energy efficiency and renewables are the main foundations towards a stable and clean future. But as, costs and yields, merits and demerits very much vary and are not proportional to each other, the government wants offers custom-made incentives.

- *Invest in a well operating European energy market*: an adequate energy-infrastructure is needed to achieve a clean, secure and affordable energy provision and the following three developments are relevant to such goal:
    - Increase share of renewables leads to unpredictable intermittent energy distribution. Major investments are necessary to overcome these disturbances.
    - More and more cross-border transport will be made possible. Gas and electricity travel greater distances by improving infrastructure, regulations, authorities and cooperation with other countries. A national energy market is no more.
    - Energy generation becomes increasingly decentralized which leads to new grid functionality. The infrastructure should allow - for example - two-way energy distribution.

In conclusion, the World Nuclear Association (WNA) summarized the policy as follows: 'In the official government statement on taking office in October 2010, the incoming prime minister noted that the security of energy supply would remain a policy spearhead, along with efforts to cut carbon dioxide emissions in line with European targets. Hence "the government will be open to issuing permits for new nuclear power plants."
The coalition agreement of the incoming government then says: "Regarding energy supply, the Netherlands must become less reliant on other countries, high prices and polluting fuels. Energy security must be increased and more attention must be paid to the potential profitability of energy. Licensing applications to build one or more new nuclear power stations that satisfy the requirements will be granted. CO_2 can be stored underground subject to strict safety standards and local support, but this question will only arise after a licence has been granted for a new nuclear power station." Also "Sustainable energy production must become competitive as quickly as possible" and subsidies for renewables will be cut back.' (WNA, 2011)

2.4 Conclusion

The worlds' human population became an urban species and developed regions became in more need of energy then their developing fellow men. The endangerment of ecosystems, air pollution and the population's health are a direct result of human, urban, economic and industrial developments. Besides a nation's energy use and provision system, harmful emissions are largely ascribed to industrial and agricultural activities, its transport and last but not least to the behaviour of its population.

Environmental problems and the exhaustion of fossil fuels increase pressure on tomorrow's energy provision, as demand increases and investments in renewables lack behind. The amounts of a city's negative emissions are considerable and the countermeasures are limited so the question rises; will policy makers both local and national be able to tackle the climate change? Only a few cities worldwide steer towards cleaner and more efficient energy provision, but little has been set to work. These critical notes are partly to blame the government as local policies or ideas are often not related to broader areas beyond the city limits and in the least to nationwide policies.

By reviewing the internationalized deregulated energy market, it becomes clear that the Netherlands form a major strategic player on European and global scale. The government's objective is to capitalize on these opportunities and to continue leadership in technology, provide employment, generate earnings and create a stable economy.

In terms of the energy transition, little change is notable because it seems that the Dutch energy market is expanding its capacity through more power stations that remarkably combust fossil fuels, namely gas and coal. This is because gas- and coal fired stations have low capital investments and low operational costs and have a short time to market.

The opportunity for new nuclear power plant exploitation is considerable, but before admitting nuclear technology, it is necessary to understand the industry, the on-going developments and its consequences. The next chapter will explain nuclear technology, its nuclear fuel cycle, its waste management and its cost structure with all merits and demerits to provide profound insight and support the necessary reasoning.

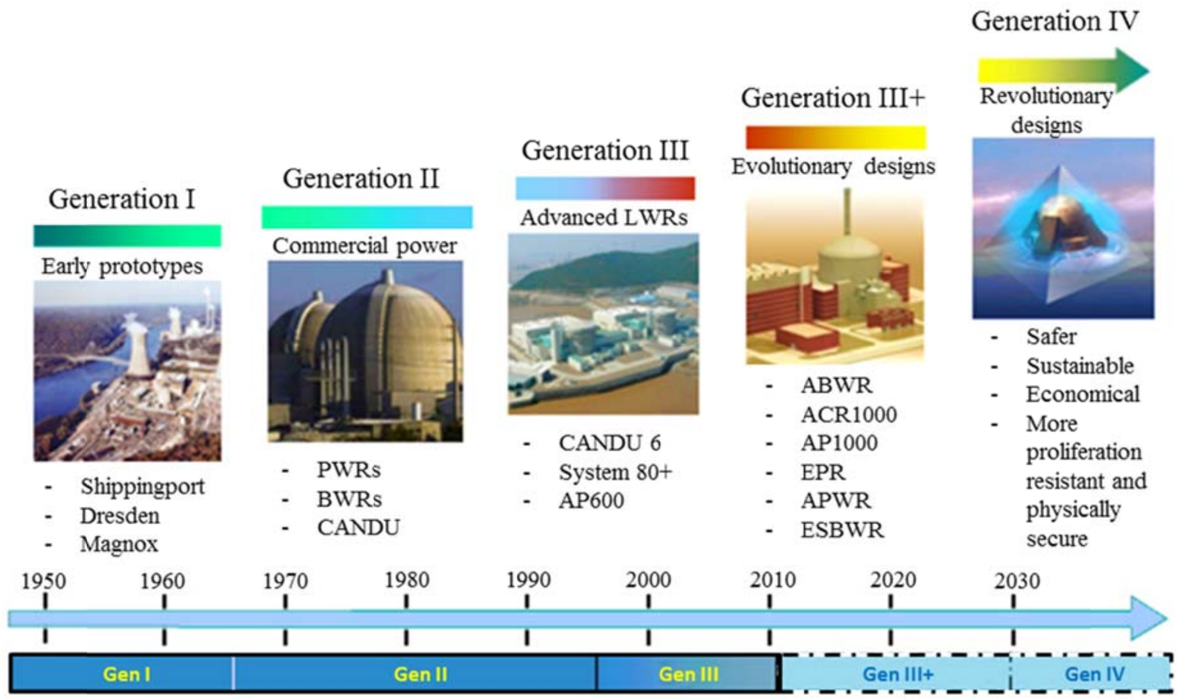
3 Nuclear choice

Fossil fuel exhaustion, air pollution and energy security became internationally more stringent over the recent years and nuclear power was set on the political agendas again. Nuclear power is considered a very practical option in generating tremendous amounts of electrical energy from low amounts of fuel and with minimum environmental harm. Although the advantages are clear, nuclear power has not been a large contributor to the global electrical energy supply. At this moment, nuclear power globally increases, however its share in total generation falls (IEA, 2009c). Thereby, nuclear power is expected to increase largely in all major regions except Europe. One could think of several reasons that cause such small increments but primarily they come down to economic considerations and anti-nuclear sentiments.
This chapter seeks to explain how future nuclear power technology has to cope with arguments like these. First will be explained what the development objectives of next generation nuclear power plants are, followed by a brief explanation of the physics within a reactor. Then, the fuel cycle differences are explained with their advantages and disadvantages and the choice for the LFR system will be pointed out. The chapter finalizes with a review on the Dutch nuclear energy program and the Dutch public opinion.

3.1 Generation IV Nuclear Energy Systems

As explained in the introduction, nuclear power systems need to be advanced to meet future needs. To support these advancements, several nations cooperating as the Generation IV International Forum (GIF) have formed a framework for international cooperation in research. They stated their intentions and research objectives in a technology roadmap that serves a future generation - Generation IV - nuclear energy systems. The Generation indication stands for the contemporary nature of the nuclear reactor design and stage of technology. Figure 3.1 gives an overview of the generations of the nuclear power generation systems.

Figure 3.1: Generations of nuclear energy



Adapted from: www.gen-4.org

The GIF roadmap describes the generations as follows: ‘the first generation was advanced in the 1950s and 60s in the early prototype reactors. The second generation began in the 1970s in the large commercial power plants that are still operating today. Generation III was developed more recently in the 1990s with a number of evolutionary designs that offer significant advances in safety and economics, and a number have been built, primarily in East Asia. Advances to Generation III are underway, resulting in several (so-called Generation III+) near-term deployable plants that are actively under development and are being considered for deployment in several countries. New plants built between now and 2030 will likely be chosen from these plants.' (GIF, 2002)

3.1.1 Generation IV research and development goals

The goals for Generation IV (henceforth: Gen IV) nuclear energy systems imply the needs for improved waste management, a minimum of environmental impacts, effective fuel utilization and the development of new energy products that can expand nuclear energy’s benefit beyond electrical generation. The GIF has established multiple objectives regarding the Research Design and Development (RD&D) towards these needs. These objectives serve as connecting thread for developing future Gen IV systems and are ought to stimulate the search for innovative nuclear fuel cycles and reactor technologies. The goals from the GIF roadmap (2002) are as follows:

- *Sustainability–1*: Generation IV nuclear energy systems will provide sustainable energy generation that meets clean air objectives and promotes long-term availability of systems and effective fuel utilization for worldwide energy production.
- *Sustainability–2*: Generation IV nuclear energy systems will minimize and manage their nuclear waste and notably reduce the long-term stewardship burden, thereby improving protection for the public health and the environment.
- *Economics–1*: Generation IV nuclear energy systems will have a clear life-cycle cost advantage over other energy sources.
- *Economics–2*: Generation IV nuclear energy systems will have a level of financial risk comparable to other energy projects.
- *Safety and Reliability–1*: Generation IV nuclear energy systems operations will excel in safety and reliability.
- *Safety and Reliability–2*: Generation IV nuclear energy systems will have a very low likelihood and degree of reactor core damage.
- *Safety and Reliability–3*: Generation IV nuclear energy systems will eliminate the need for offsite emergency response.
- *Proliferation Resistance and Physical Protection–1*: Generation IV nuclear energy systems will increase the assurance that they are a very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.

The sustainability goals in particular are interesting because the aspects of economics, safety, and reliability and proliferation resistance may appear obvious. The true novelty namely is its sustainable properties in terms of future fuel utilization and relieving the burden of long living waste.

A closer review of the GIF's sustainability goals learns that:

'S*ustainability is the ability to meet the needs of the present generation while enhancing the ability of future generations to meet society's needs indefinitely into the future*'.

In the GIF's roadmap, sustainability goals are defined with focus on waste management and resource utilization.
Their primary sustainability goals are:

- Extending the nuclear fuel supply into future centuries by recycling used fuel to recover its energy content, and by converting natural uranium (i.e. non enriched U^{238}) to new fuel;
- Having a positive impact on the environment through the displacement of polluting energy and transportation sources by nuclear electricity generation and nuclear-produced hydrogen;
- Allowing geologic waste repositories to accept the waste of many more plant-years of nuclear plant operation through substantial reduction in the amount of wastes and their decay heat ;
- Greatly simplifying the scientific analysis and demonstration of safe repository performance for very long time periods (beyond 1000 years), by a large reduction in the lifetime and toxicity of the residual radioactive wastes sent to repositories for final geologic disposal.

3.2 The physics of a nuclear reactor

To comprehend how the sustainability goals will come to practice, it is necessary to understand more about the nuclear fuel cycle and about the fissioning of nuclei within reactors.

Neutron physics is the starting point for all the energy produced inside a reactor. When a neutron passes a heavy nucleus of uranium (e.g. U^{235}) it may be captured by the nucleus. The addition of the neutron forms a new compound nucleus, which may or may not be followed by fission. But in certain cases, fission follows. Whether fission takes place – and whether a neutron is captured at all – is dependent on the velocity of the passing neutron and on the heavy nucleus involved. For this interaction the following basic rule applies: low energy neutrons called 'slow' or 'thermal neutrons' have a velocity around 2km/s. Slow neutrons only fission the less heavier nuclei that contain an odd number of neutrons (e.g. U^{233}, U^{235}, Pu^{239}). The fissioning of more heavy nuclei that contain an even number can only occur if the energy of the neutron is higher. These high energy neutrons have a velocity around 20,000km/s. Therefore these neutrons are called 'fast neutrons' (Hore-Lacey, 2006).

A nuclear reactor facilitating fission by slow neutrons implies a 'thermal neutron spectrum' hence 'thermal reactors'. Typical thermal reactors are light water reactors (LWR). In a LWR the water that transfers heat from the core and cools the nuclei is also used to slow down (moderate) the neutrons to proceed with fission. Consequently, a reactor operating by fast neutrons implies a 'fast neutron spectrum' hence 'fast reactors'. Fast reactors do not have the need to moderate the neutrons and therefore apply core cooling by either some specific types of liquid metal or gas as these coolants have minimal moderating properties. The liquid metals typically used are sodium or a sodium-potassium mixture, lead or a lead-bismuth mixture.

3.2.1 Nuclear fuel feed and spent fuel discharge

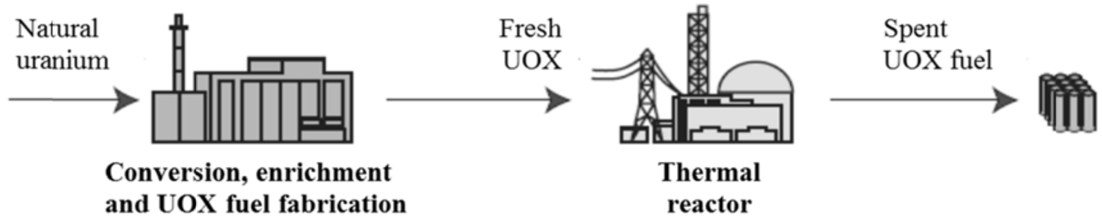
In general, thermal spectrum reactors are fed with uranium. The fuel that goes to the reactor contains U^{235} that is lighter and more unstable thus easier to fission. U^{235} appears in natural uranium (U^{238}) for about 0.7%. As thermal reactors mostly fission the U^{235}, the level of U^{235} is slightly enriched to 3-5% in order to (1) provide more fissile material (2) make it easier to fission. The spent fuel discharged from the reactor contains some unfissioned U^{235} (<1%), minor actinides (MAs; transuranic elements other than uranium or plutonium) and other fission products (FPs). These transuranics are formed because of neutron capture and decay of nuclei, for example, the abundant U^{238} becomes the fissile isotope of plutonium Pu^{239} after some intermediate forming and decay of other isotopes. A part of the Pu^{239} is fissioned, a part becomes Americium (Am^{241}) by further neutron capture and a part of the Pu remains. Other important MAs are that of Neptunium (Np^{237}) and Curium (Cm^{243}). These are very long living isotopes and therefore important because they are responsible for the high level of radio toxicity which makes long term waste disposal difficult.

In a fast reactor on the other hand, the predominant fuel is Pu^{239}. These reactors are a different technology and utilize much more of the natural uranium than their thermal counterparts that merely use the isotope U^{235}. Therefore it can be said that fast reactors are up to 100 times more efficient at converting fertile material than ordinary thermal reactors because of the arrangement of fissile and fertile materials (Hore-Lacey, 2006).
A fast reactor can produce more fissile material than it consumes. This is generally done by adding a fresh blanket of U^{238} around the plutonium core that captures neutrons from the fissioning so it becomes fissile Pu^{239}. This process is called 'breeding' and reactors that are designed to operate in such conditions are called 'fast breeder reactors' or simply 'breeders'. If they are designed to consume plutonium at a higher rate than they produce, these reactors are called 'burners' or 'incinerators'. Above all, in a fast reactor, shares of minor actinides can be mixed with the fuel to burn along with the plutonium. This property can make fast reactors so especially sustainable in terms of long living waste management.
For a long time, the focus of RD&D on fast reactors was on the potential of breeding, but with the low uranium prices and the urge to remove plutonium from military weapons, the short-term interest now is their role as burners (Hore-Lacey, 2006).

3.2.2 Fuel cycles

The most common fuel cycle today is the open fuel cycle with reprocessing (see figure 3.2) and is used for thermal reactors. In the open or once through fuel cycle, uranium is first mined, than conversed to a powdery substance that is ready for enrichment. After enrichment, the uranium is sent to a fuel fabrication facility where it is processed into fuel rods containing uranium oxide fuel (UOX). All described fuel cycle steps up to and including the preparation of the fuel rods, are denominated by the term 'front end'. After the fuel is being discharged, the spent fuel remains in intermediate storage at the NPP site to cool down before it can be processed any further. After the spent fuel is cooled down, it can be reprocessed to extract the remaining U^{235}. It then can be encapsulated and the waste can be disposed. These fuel cycle steps are denominated as 'back end'.

Figure 3.2: The open fuel cycle

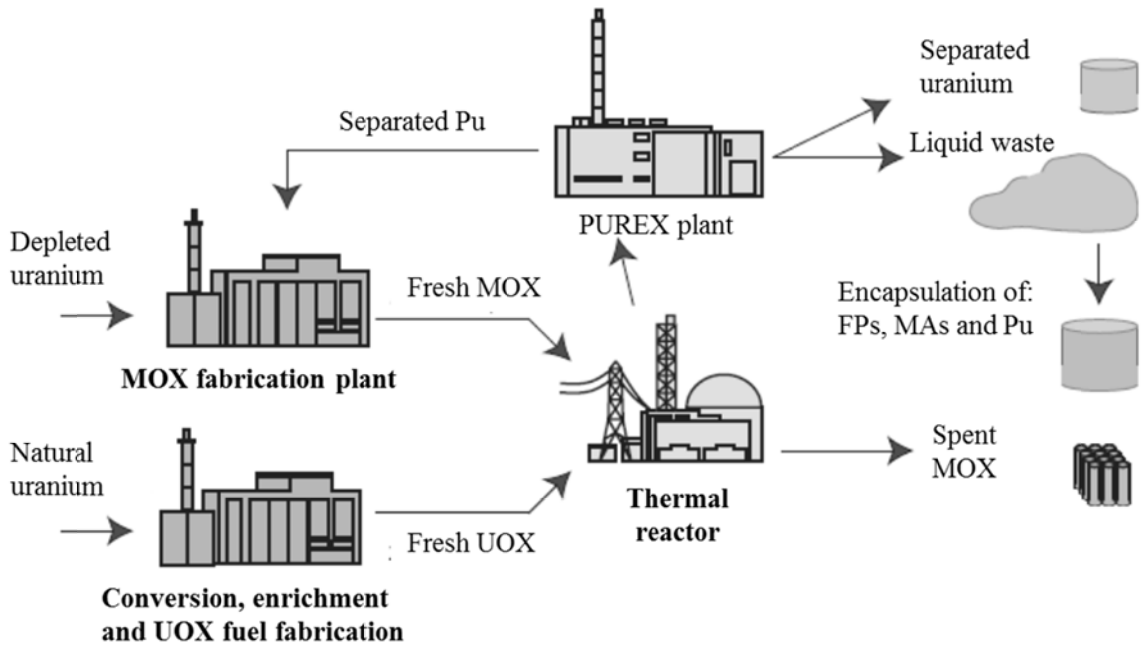


Adapted from: MIT, 2003 p.30

In the Netherlands, used nuclear fuel from the Borssele reactor is being recycled at La Hague, France. Areva NC, operators of La Hague, hold a contract to recycle Borssele used fuel until 2015. Some recycled uranium has been used in the plant for several years and the operator is now seeking approval to use mixed oxide fuel (MOX) that contains 5.4% of fissile Pu content as 40% of the fuel load (WNA, 2011).

The separation and recycling of spent fuel UOX and MOX is typically done in the closed fuel cycle. The spent fuel discharged from the reactor is reprocessed in a PUREX (Plutonium Uranium Extraction) plant. Here, the fuel is partitioned into uranium (U) and plutonium (Pu) suitable for fabrication into UOX or MOX to recycle back into a reactor (see figure 3.3). The MOX fuel, containing high levels of plutonium, is fed back into the reactor. The share of MOX however remains lower than the share of UOX as regular thermal reactors could not maintain a chain reaction from plutonium only. The closed fuel cycle is thus a more efficient system for the use of uranium originally extracted (by about 30% in energy terms) (Hore-Lacey, 2006).

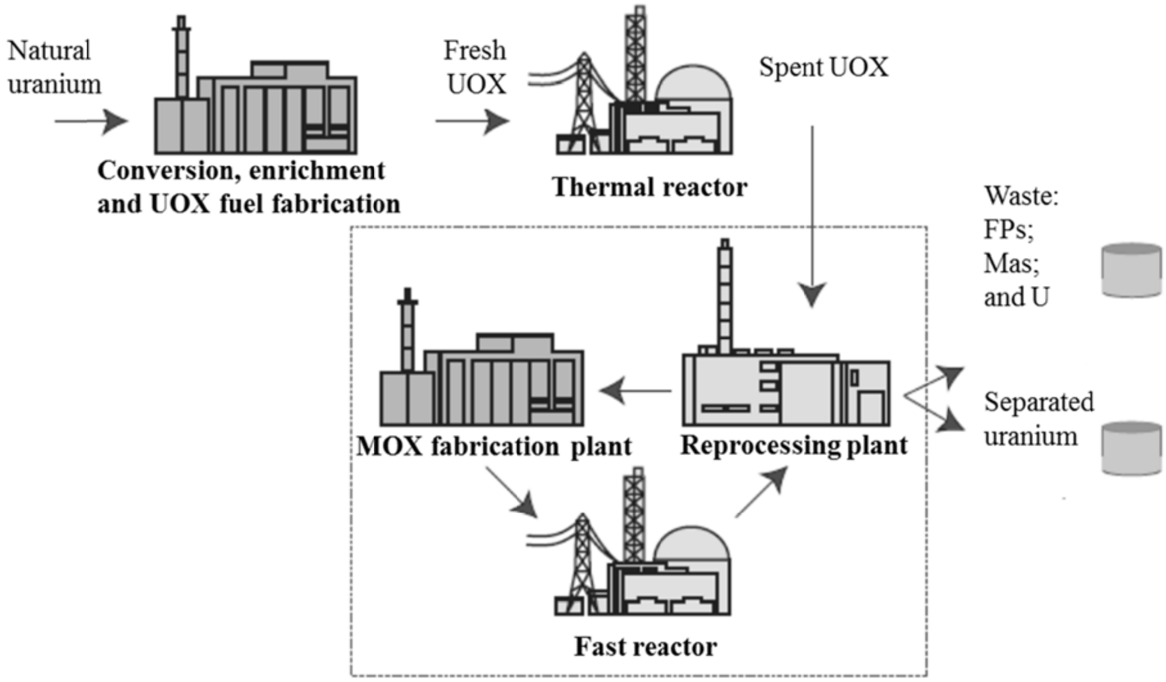
Figure 3.3: The closed fuel cycle with partly recycling



Adapted from: MIT, 2003 p.30

In the future, closed fuel cycles could include the use of a dedicated fast reactor (see figure 3.4) that can be used to breed fissile material or can be used for the transmutation of selected isotopes that have been separated from spent fuel, burning as it were, the highly radioactive material. When the LFR is designed to transmute actinides from spent LWR fuel, nearly all long-lived actinides can be transmuted to short-lived isotopes, which would (1) reduce the amount of radioactive waste that needs deep repository to a fraction of what is needed for once-through cycle; (2) by removing the actinides (Am, Np, Cm) the radioactivity would be significantly reduced within 100 years (Hore-Lacey, 2006).

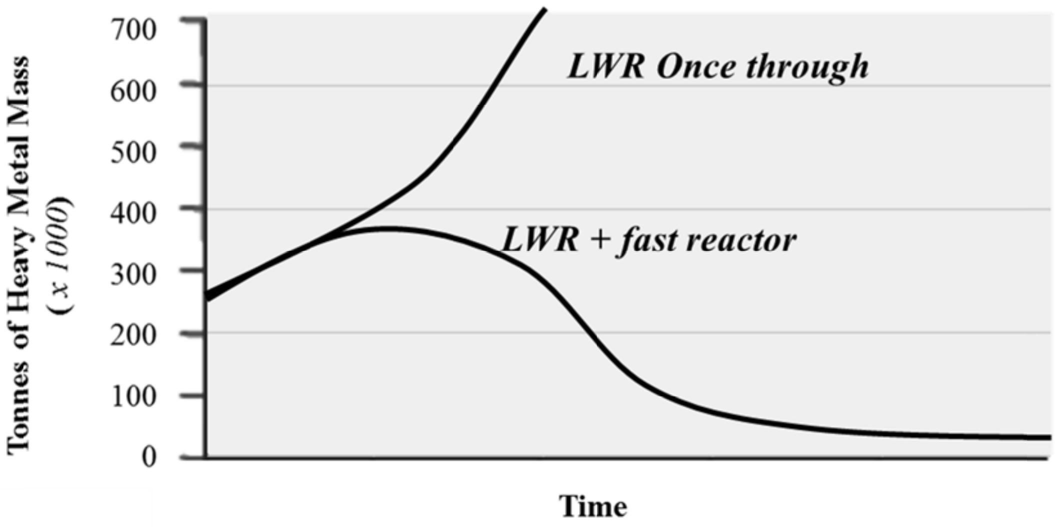
Figure 3.4: The closed fuel cycle with fully recycling



Adapted from: MIT, 2003 p.31

The sustainable property of the closed fuel cycle with fully recycling has a very evident effect on permanent waste storage as shown in figure 3.5.

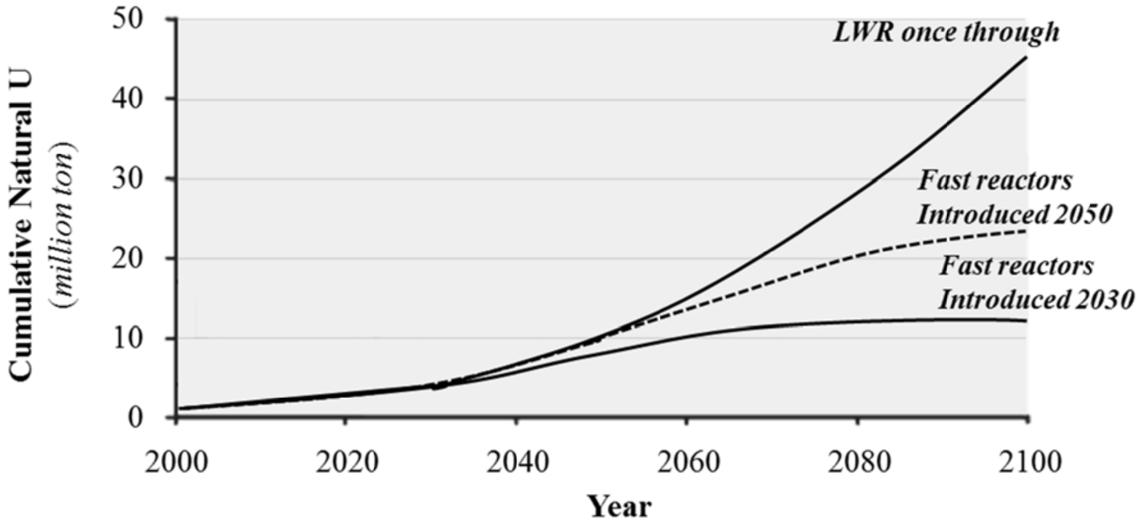
Figure 3.5: Spent fuel inventory with and without the introduction of fast reactors



Source: Generation IV International Forum, 2002 p.13

Since fast reactors use their fuel more efficiently, ores of lower uranium concentrations could become economically feasible and as a direct consequence the available resources would increase further. When the dedicated fast reactor is used in such fuel cycles, uranium fuel utilization becomes almost one fifth by 2100 compared to the current LWR once through consumption rate, extending the amount of resources for many decades to come. This is shown in figure 3.6

Figure 3.6: Worldwide uranium resource utilization with and without fast reactors



Source: Generation IV International Forum, 2002 p.13

Although the closed fuel cycle with actinide burning shows tremendous waste management benefits, some critical notes are placed. According to the MIT study, current recycling infrastructure in Europe Japan and Russia seems not yet proliferation proof (MIT, 2003) and the expenses of closed fuel cycles do not cover direct long-term geological storage. They also state that, because there is an adequate amount of uranium resources for global nuclear expansion for over at least the next 50 years, the best choice would be the open, once-through fuel cycle.

This best choice can be further explained by the research performed by Bunn et al (2003). They have investigated the economic turning point or 'break-even point' when the costs of recycling outweigh the costs of direct disposal. They state that:
'From the dawn of the nuclear age, the nuclear industry believed that uranium was relatively scarce and that the number of reactors would grow rapidly, and as a result the price of uranium would increase quickly. Hence, the industry projected that there would be a rapid transition from LWRs to FRs. This transition to FRs has taken much longer than once expected. Uranium has turned out to be abundant and cheap, the world's use of nuclear energy has grown much more slowly than expected, and FRs so far have been more expensive and problematic than anticipated.' (Bunn et al, 2003)

Bunn et al concluded the following break even points:
'At a reprocessing price of US$1000 per kilogram of heavy metal (kgHM) and with our other central estimates for the key fuel cycle parameters, reprocessing and recycling plutonium in existing LWRs will be more expensive than direct disposal of spent fuel until the uranium price reaches over US$360 per kilogram of uranium – a price that is not likely to be seen for many decades, if then.' (Bunn et al, 2003)

'Reprocessing and recycling plutonium in FRs with an additional capital cost, compared to new LWRs, of US$200/kWe installed will not be economically competitive with a once-through cycle in LWRs until the price of uranium reaches some US$340/kg, given our central estimates of the other parameters. Even if the capital cost of new FRs could be reduced to equal that of new LWRs, recycling in FRs would not be economic until the uranium price reached some US$140/kg.' (Bunn et al, 2003)

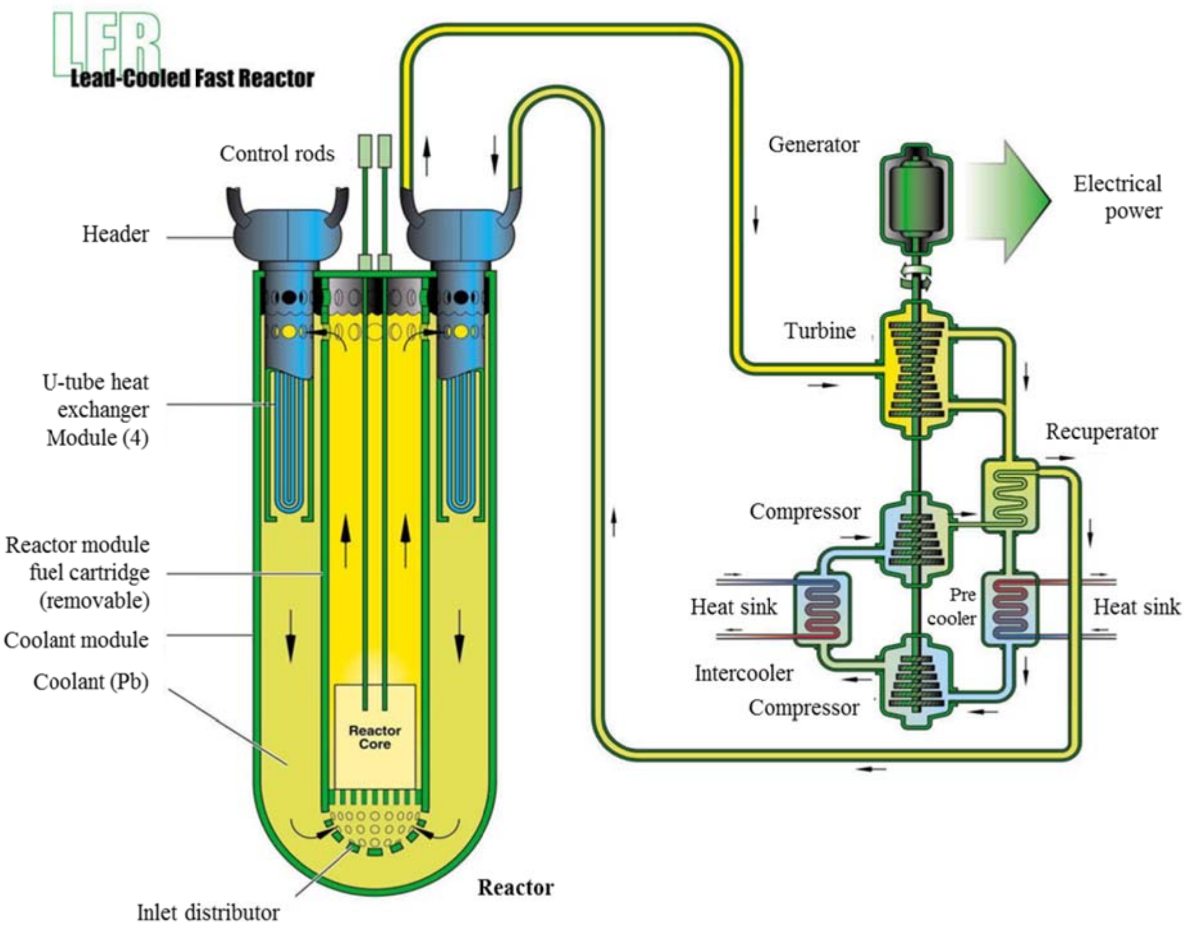
Known uranium resources at the moment are extractable at 80 US$/kg (Hore-Lacey, 2006) and more hard to get speculative uranium resources might be extracted up to US$130/kg (IAEA, 2007). Unfortunately, the quantity of these resources and their actual depletion cannot be stated further as the intensity of the exploration effort has been low between the early 1980s and 2005 (Hore-Lacey, 2006). Also, there is no telling to what extent known or hard to get resources are measured. Uranium is a very abundant and common metal like zinc or tin and is a constituent of most rocks and even seawater, which holds 0.003 ppm (parts per million) uranium (Hore-Lacey, 2006). Japanese research efforts have shown it is extractable at about US$500/kg (MIT, 2003). Bunn et al state that these publications are quite doubtful when considering total life cycle costs such as return on investments and costs of capital like taxes and that the price – at least for European and US markets – is more likely between 1200 to 1700 US$/kg (Bunn et al, 2003). In conclusion, common notions exist that the available 'cheap' uranium resources will be sufficient for at least throughout the 21st century concerning the current installed nuclear capacity (Bunn, et al, 2003).

3.3 The Lead-cooled Fast Reactor system

For this research effort, the Lead-cooled Fast Reactor (LFR) (see figure 3.7) was considered because it has some unique and promising options over other prospective nuclear power plants, as will be explained below.

‘The LFR system features a fast-neutron spectrum and a closed fuel cycle for efficient conversion of fertile uranium and management of actinides. A full actinide recycle fuel cycle with central or regional fuel cycle facilities is envisioned. The system uses a lead or lead/bismuth eutectic liquid-metalcooled reactor.

Figure 3.7: Schematic resemblance of a generic LFR system



Source: Generation IV International Forum, 2002 p.27

Options include a range of plant ratings, including a *battery* of 50–150 MWe that features a very long refuelling interval, a modular system rated at 300– 400 MWe, and a large monolithic plant option at 1200 MWe. The term *battery* refers to the long-life, factory fabricated core, not to any provision for electrochemical energy conversion. The fuel is metal or nitride-based, containing fertile uranium and transuranics. The most advanced of these is the Pb/Bi battery, which employs a small size core with a very long (10–30 year) core life. The reactor module is designed to be factory-fabricated and then transported to the plant site. The reactor is cooled by natural convection and sized between 120–400 MWth, with a reactor outlet coolant temperature of 550°C, possibly ranging up to 800°C, depending upon the success of the materials R&D. The system is specifically designed for distributed generation of electricity and other energy products, including hydrogen and potable water.'(GIF, 2002)

'The LFR system is top-ranked in sustainability because a closed fuel cycle is used, and in proliferation resistance and physical protection because it employs a long-life core. It is rated good in safety and economics.' (GIF, 2002) The safety is enhanced by the choice of a relatively inert coolant (Pb) compared to sodium for example.

The other prospective Gen IV reactors in term have other characteristics beneficial over that of the LFR system. The decisive factors that are:

- construction and exploitation where only a small area or footprint is available;
- the small modular built types allow it to be shipped to regions where there is limited or no sufficient construction infrastructure;
- smaller units can fit lower voltage power grids;
- lead shields γ-rays effectively;
- the cost reduction achieved by a compact plant design;
- the plant footprint has been reduced due to the elimination of the intermediate circuit and the reduced-height design of components.

For further figures of the LFR system, data of the European Lead-cooled fast reactor SYstem (ELSY) design is adopted as a reference design. All further used data, characteristics and calculations are based on this specific ELSY design. Its characteristics are briefly explained below.

'The ELSY reference design is a 600 MWe pool-type reactor cooled by pure lead. The ELSY project demonstrates the possibility of designing a competitive and safe fast critical reactor using simple engineered technical features, whilst fully complying with the Generation IV goal of sustainability and minor actinide (MA) burning capability. Sustainability was a leading criterion for option selection for core design, focusing on the demonstration of the potential to be self-sustaining in plutonium and to burn its own generated MAs. To this end, different core configurations have been studied and compared. Economics was a leading criterion for primary system design and plant layout. The use of a compact and simple primary circuit with the additional objective that all internal components be removable, are among the reactor features intended to assure competitive electric energy generation and long-term investment protection. Low capital cost and construction time are pursued through simplicity and compactness of the reactor building (reduced footprint and height). The reduced plant footprint is one of the benefits coming from the elimination of the Intermediate Cooling System, the low reactor building height is the result of the design approach which foresees the adoption of short-height components and two innovative Decay Heat Removal (DHR) systems.' (Alemberti et al, 2009)

The design owes its safety the Pb coolant which is relatively inert with air and water. It has a very high boiling point of approx. 1780 °C. The reactor is designed in such way that the lead can circulate naturally, in case lead pumps within the reactor fail. This together with the high boiling point makes the reactor highly resistant against unwilling interruption of any mechanical parts for what reason ever.
The medium size design allows decay heat to be removed by natural circulation. This passive DHR system increases safety even more, as with larger plants, pumps are still required to remove the decay heat.

Its fuel economy can be designed to fission MOX fuel and burn plutonium, fission products and actinides. The research data of the concerning LFR provide that when loaded with 5% of minor actinides homogeneously admixed to start-up fuel, it would burn about 85-90 kg of minor actinides per year (equivalent to annual minor actinide production in about 2.5 LWRs of 1 GWe capacity each) (Alemberti et al, 2009). The concerning LFR further burns its own produced MAs. It is also possible to have it operate in 'breeder' mode; however, it is not the objective for the system concerned in this research. Furthermore, the ELSY reactor is expected to be operational around 2040.

3.4 Dutch nuclear energy program

As stated in chapter 2, nuclear energy makes out 1.3% of the Dutch energy provision. Speaking in sheer electricity terms this share is higher and the currently operated Borssele reactor provides about 4% of total generation, namely 4.1 TWh net in 2007 (WNA, 2011). In 2007, a total of 103 TWh gross was generated. Natural gas provided 60 TWh, and coal 28 TWh. Renewables (mostly biomass) added 8.7 TWh. Another 21.5 TWh net of electricity is imported, mostly from Germany, and since some of that is nuclear-generated, official statistics put the nuclear share at 9-10%. Per capita consumption is about 6500 kWh/yr (WNA, 2011).

The Dutch interest in nuclear reactors started at the very beginning of the nuclear era in the last century. A brief review on the history and currently operated nuclear reactors is given next, followed by the Dutch nuclear energy and waste management policy. These are mostly quoted from the World Nuclear Association (WNA) that keeps a track record on the Dutch nuclear energy program.

3.4.1 History

'Back in the '50's the Ministry of Economic Affairs had a strategy to develop a national industry capable of designing, manufacturing and exporting nuclear power technology. The ultimate aim was that nuclear power would be introduced from about 1962 to gradually replace much fossil fuel electricity generation. Hence the Reactor Centrum Netherlands (RCN) was established.
In 1955 construction began on the Netherlands' own research reactor, the High Flux Reactor (HFR) at Petten. HFR was intended to help the country gain knowledge of nuclear technology and operations through materials research.'(WNA, 2011)

For scientific education purposes, two reactors were built in the Netherlands. The first was the 2MW Higher Education Reactor (HOR) (Dutch: Hoger Onderwijs Reactor) built at the former 'Technische Hogeschool Delft' now University of Technology Delft (TUD). Its construction began november 1958. This reactor is still operating today and is of major importance to knowledge about radio technics and therapy and to the training of Dutch nuclear scientists (Kernenergie in Nederland, n.d.).

The second educational reactor was constructed in June 1966 at the former 'Technische Hogeschool Eindhoven' (THE) now University of Technology Eindhoven (TU/e). It concerned a 10kW reactor which was named ATHENE (Atomic reactor THE NEtherlands). It was decommissioned in 1973 as the Scientific Council for Nuclear Energy advised the government it had too little scientific contribution (TU/e, 2011).

‘In May 1965, construction started on the first nuclear power reactor in the Netherlands, a 55 MWe natural circulation boiling water reactor at Dodewaard. The plant, intended as a test-bed for the national nuclear power industry, was connected to the grid in October 1968. It was operated until 1997, when it was shut-down for economic reasons. The Dodewaard reactor shut down in 1997 and is being decommissioned. In 2003 the last fissionable material was removed and parts of the plant were demolished. The main part will be sealed and monitored to 2045, before being demolished.

The next nuclear power project was a commercial 452 MWe pressurised water reactor at Borssele, in the south west of the country. Construction started in July 1969 and the plant was connected to the grid in July 1973. It was designed and built by Germany's Kraftwerk Union (Siemens). It is operated by Electricity Generating Company for the Southern Netherlands (EPZ) and was owned by Essent and Delta Energie (50% each). In 2006, following an extension of its operating life to 2033, a turbine upgrade boosted its capacity from 452 to 485 MWe.’(WNA, 2011)

3.4.2 Future nuclear expansion plans

‘In September 2008 Delta (50% owner of EPZ and Borssele) announced that it would build a second unit at Borssele, of 1000-1600 MWe. In June 2009 it embarked upon seeking preliminary approvals for it from the Ministry of Housing, Spatial Planning and the Environment. Delta proposed to start building in 2013 and have a 1600-2500 MWe plant operational in 2018, using MOX fuel. Delta has started environmental assessment procedures, and after talks with potential partners in November 2010 signed an agreement with EdF (Électricité de France). The partnership will now explore incorporation of a joint development company. EdF said it was prepared to invest EUR 2 billion in a minority share of a new plant at Borssele. Should the project go ahead, it may include third parties as investors and to contract for the plant's output. Following the May 2011 buyout of Energy Resources Holding (ERH), RWE was reported as offering to underwrite 20% of the project.
When German utility RWE agreed to buy Essent for EUR 8.35 billion in 2009 it announced that it was prepared to build new nuclear capacity in Netherlands. Essent's share of EPZ was then placed into a new company - Energy Resources Holding (ERH) - owned by the provincial and municipal authorities comprising Essent's original shareholders. In September 2010 ERH applied to build a new nuclear plant at Borssele, quite separate from the Delta proposal. This was for a plant up to 2500 MWe, using one or two Westinghouse AP1000 reactors, an EPR or a BWR (Boiling Water Reactor). Construction was envisaged from 2015, for operation in 2019.’ (WNA, 2011)

3.4.3 Nuclear energy policy

‘In the early 1960s, large natural gas reserves were discovered in The Netherlands. In combination with the public opinion impact of the Chernobyl accident, interest in nuclear energy diminished. In 1986, a new build project was shelved by order of the government.

In 1994 the Dutch parliament voted to phase out the Borssele nuclear power plant by 2003. The government however ran into legal difficulties to implement that decision. In 2003, the ruling conservative government coalition moved the closure date back to 2013, and in 2005 the phase-out decision was abandoned.

In June 2006, the Dutch government concluded a contract with the Borssele operators and shareholders. The reactor would be allowed to operate until 2034 on certain conditions: it would be maintained to the highest safety standards, and the stakeholders, Delta and Essent, agreed to invest EUR 250 million towards sustainable energy projects. The government added another EUR 250 million, in the process avoiding the compensation claim they would have faced had they continued towards early shutdown.

In September 2006 the environment minister on behalf of the economics minister submitted to parliament a document entitled, *Conditions for New Nuclear Power Plants.* An accompanying statement said that the government wanted to move to a sustainable energy supply and that the abandonment of its earlier phase-out policy (deferring Borssele's shutdown to 2033-34) was part of a transition strategy, and nuclear power could reduce carbon emissions. A new nuclear reactor could also be fitted into this transition model.

Any new reactor must be a Generation III model with levels of safety being equivalent to those of Areva's European Pressurized water Reactor (EPR), at a coastal site. Before its operation, and no later than 2016, the government must decide on a disposal strategy for existing high-level waste. Used fuel should be stored until 2025, when a choice would be made between direct disposal, reprocessing, or partitioning and transmutation. Plants should be dismantled promptly after closure, and decommissioning funds clearly earmarked. Uranium should be sourced from certified, environmentally responsible mining operations, with in-situ leaching preferred due to their low environmental impact.' (WNA, 2011)

3.4.4 Nuclear waste management

'In the 1970s the Dutch government adopted a policy of reprocessing used nuclear fuel from both the Borssele and Dodewaard reactors. In 1984 it decided on a policy of long-term (100 years) interim storage of all the country's radioactive wastes; and a research strategy for their ultimate disposal. This led to the establishment of the Central Organization for Radioactive Waste (COVRA), based at Borssele, close to the nuclear power station. A low- and intermediate-level radioactive waste (LILW) management centre was commissioned at Borssele in 1992 which provides for storage of those materials.' (WNA, 2011)

In September 2003, COVRA's HABOG facility - an interim storage for high-level waste (HLW) was commissioned by Queen Beatrix. HABOG has two compartments, one for medium-level waste such as canisters containing fuel element claddings after reprocessing of their uranium contents; and one for the vitrified HLW returned after used fuel reprocessing (fission products and transuranics). It stores all the HLW from Dodewaard fuel reprocessed at Sellafield in UK, and all the waste returned from reprocessing Borssele fuel at La Hague. A system of natural convection operates in the second compartment to cool the heat-generating HLW.

Government policy is to eventually store HLW underground and to move towards that goal in a way such that each step is reversible. In 2001, the Government-sponsored Committee on Radioactive Waste Disposal (CORA) concluded that geological retrievable disposal is technically feasible in a safe manner, on several sites in the Netherlands.

In 2006, the Government proposed to make a decision about the siting for final disposal by 2016.

3.4.5 Public opinion

Nuclear technology reaches the public debate form time to time and today even more than ever, mostly fed by the media .For decades now the debate is going on like a needle of a record player that is stuck in the same groove. Remarkable is that the debate remains ever polarized; you are either in fond of or against it. Even with nuclear power proven to have the smaller accident rates and safety risks of the full energy chain than that of coal and gas-fired generation and even hydro energy, the public perception is different. (ECF, 2010, ECN 2010c, MIT, 2003). The risk of accidents remains, but the likelihood of such events have reduced significantly over the past decades and will decrease even more in the future.

In 2009, the Smart Agent Company (SAC) performed a survey among 1010 Dutch citizens regarding their perception towards nuclear power. The most important conclusion is that the perception is interrelated between three factors, namely: *fear*, *knowledge*, *trust*.
Unfortunately, the research not elucidated if more knowledge would lead to more trust and to less fear (SAC, 2009).
For most respondents of this survey, a hopeful future scenario for the time being is one with nuclear power. However, because most respondents do not perceive nuclear power plants as inherently safe, it is perceived as a 'necessary evil'. Furthermore, a lot of respondents indicate that their knowledge of nuclear power is insufficient to comprehend the technology and to make a well-considered judgment. The foremost conclusion is that citizens are ready to go into the nuclear debate, as long it is placed within the context of all energy options. Most respondents also feel that something must happen to ensure energy provision in the future, but they experience that little has been done yet.

Further, the survey also proposed a Gen IV nuclear reactor to the respondents. This scenario was considered the most favourable of them all. An important note is that the survey explained the citizens that of all reactor alternatives, a Gen IV reactor is the most safe and least polluting regarding radioactive waste. As most respondents were convinced that nuclear power remains necessary – be it necessary evil or not – to fulfil future energy needs. Therefore the commotion around nuclear power for them was not the choice: 'yes' or 'no', but: 'what is the safest, least polluting option'. Below follows a quote from one of the respondents:

'*...it would be tremendous if energy could be derived solely form environmental friendly resources, but unfortunately that is impossible. Then, the criteria are as safe as possible thus with a generation IV...*'

Respondents that indicated that a Gen IV is the most desirable, feel that common sense tells them to wait until an inherently safe Gen IV reactor comes to market. For them, the replacement of Borssele or expansion with any other Gen III or III+ is no real advancement, bearing in mind the future arrival of Gen IV. Although this positive attitude towards Gen IV systems, it remains that people have the hope that in the next decades, other solutions will be found and that nuclear power will be phased out as quickly as possible. The respondents have trust in technology advancements and expect major breakthroughs that yet need to be discovered.

3.5 Conclusion

The future of nuclear power, as seen from the GIF point of view, looks promising. Their roadmap indicates a short time to market of these Gen IV systems, although 2030 might be a bit too optimistic.

Fast reactors hold an incredible potential regarding uranium resource utilization and waste management. As explained, in closed cycles with recycling, almost all of the uranium is utilized instead of the U^{235} isotope alone and the spent fuel in the fuel cycles' waste stream will contain less actinides which will significantly reduce the long-term radioactivity of the nuclear waste. It also relieves the current storage capacity as the same amount of electricity can be generated with less waste.

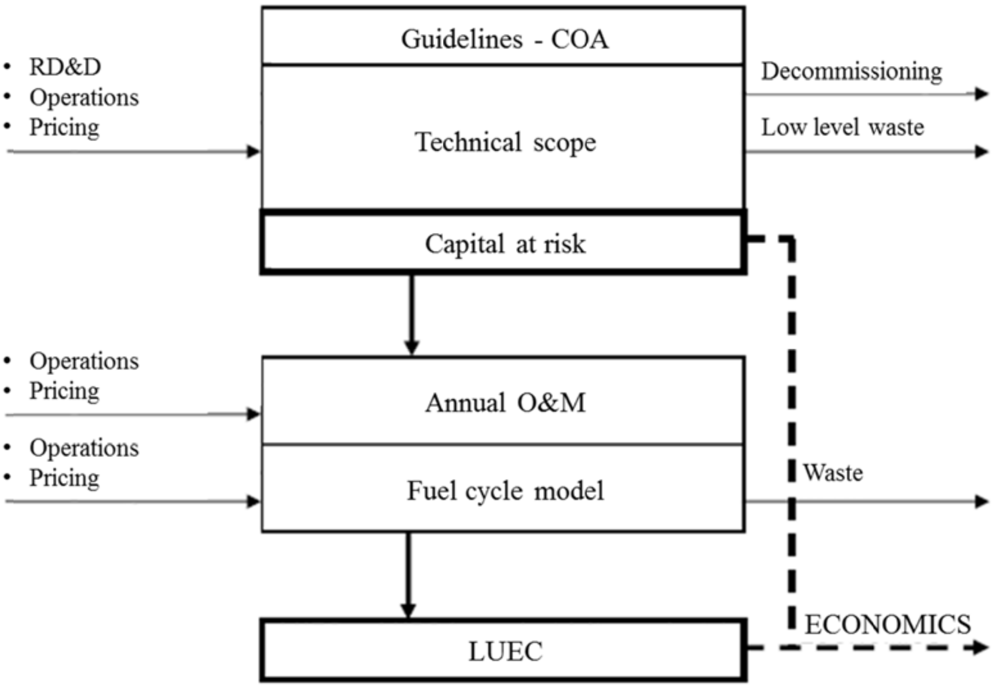
In the Netherlands, several market parties have indicated their interest in building a new nuclear reactor in the country. Because of exhaustion of some of the natural gas fields, and increasing public acceptance of the environmental advantages of nuclear power, there has been a marked shift in the position of some political parties in favour of nuclear power expansion. This means that the Dutch government is opposed with waste management for centuries. For that reason the LFR can provide a sustainable solution.

Public acceptance will also be critical to expansion of nuclear power. The SAC survey results show that the public see nuclear power necessary to ensure energy provision in the future, but it still remains a necessary evil. The amount of respondents that felt they could not judge nuclear choices based on their knowledge, suggests that further public education may be necessary.

4 Integrated Nuclear Energy Economics Model

To determine the economics of Gen IV systems, the GIF has set up the Economic Modelling Working Group (EMWG). The EMWG is in charge of the development of future generation cost estimation methods. They proposed the Integrated Nuclear Energy Economics Model (INEEM). The structure of the INEEM is represented by figure 4.1 below. Their Code of Accounts (COA) system is used to calculate the costs of the concerning LFR as no data of the costs is yet available. The accounts that were used are enclosed in appendix A and are repeatedly referred to by an italicized account enumeration (e.g. capital at risk consists of *accounts 10 through 60*). The accounts are expressed by 2 digits. The first digit indicates a group; the second digit indicates the sub-component of that group (e.g. *account 1* consists of *accounts 11, 12,…, 19*).
This chapter explains every step taken to derive the costs of the LFR following the COA. The ultimate aim of the costs calculations is to determine the LFR's levelized unit of electricity costs (LUEC). The LUEC expresses the euros it costs to generate one MW of electricity. The purpose of the LUEC is that this figure makes it is now comparable to other electricity generating systems. This is important to determine its economic competitiveness.

Figure 4.1: Integrated Nuclear Energy Economics Model



Source: Generation IV International Forum Economic Modeling Working Group, 2007 p.11

4.1 EMWG Calculation method

"The EMWG was created by Generation IV International Forum (GIF) early in 2003. The Group was charged with developing a methodology to assess the progress of the Generation IV systems in achieving the economic goals established by the GIF Policy Group. The objective was to establish a simplified cost estimating methodology appropriate for Generation IV systems in various stages of development and sufficiently rigorous to promote consistent application by the systems development groups. The Economic Modelling Working

Group (EMWG) proposed a calculation method for the prospective Generation IV nuclear power plants.
To facilitate implementation of the Cost Estimating Guidelines, the EMWG developed an EXCEL based spreadsheet package, G4-ECONS. The software package facilitates the input of total capital cost at a high level to prevent the inadvertent disclosure of proprietary data. Levelized unit electric cost is also calculated. G4-ECONS provides the capability for cost estimates of systems designed for other than electricity production, such as desalination or hydrogen production." (Rasin and Ono, 2009)

4.1.1 FOAK unit

Two plant cost models will be considered, namely a first-of-a-kind (FOAK) plant, because there are no specific LFRs of this type to date and an nth-of-a-kind (NOAK) for identical follow up LFRs. Because of the goal is to find out if the LFR could be a competitive attractive option; the NOAK plant cost figures will further be used to assess its economic advantages, assuming that market parties will only opt for a LFR after it is fully demonstrated.

The FOAK (first-of-a-kind) unit is based on the following assumptions:

- The costs do not include RD&D (research development & demonstration) costs;
- Cost like site-specific licensing and construction reoccur for each plant and non-recurring reactor design certification only applies to the FOAK plant;
- The construction time is 8 years;
- New fuel facility costs are not taken into consideration and are equal to a NOAK plant;
- Standard plant costs including all engineering, equipment, construction, testing, tooling project management and other recurring costs are incurred in building identical plants;
- The reactor's average capacity factor over life is 85%;
- Overall capital contingency is 15%.

4.1.2 NOAK unit

The NOAK (Nth-of-a-kind) unit is based on the following assumptions:

- Design will be identical to the FOAK, so engineering or reactor license costs will not differ and the plant will not undergo any product improvements;
- The plant is supplied and built by the same vendors and contractor as the FOAK;
- The plant site conditions are similar to the reference site;
- The plant's construction time is 4.75 years;
- Site-specific and pre-licenced site costs are included. A generic plant approval is assumed;
- Standard plant costs including all engineering, equipment, construction, testing, tooling project management and other recurring costs are incurred in building identical plants;
- Non recurring engineering and home office services costs of the reactor manufacturer or major process equipment manufacturer will be set to zero. Any applicable recurring costs will be identified;

- Estimates are based on the experience learning curve. For each doubling of construction experience, the following factors are applied; 0.94 for equipment costs, 0.90 for construction labour and a 10% reduction in material costs for multi-plant orders;
- The reactor's average capacity factor is 90%;
- Overall capital contingency is 10%.

4.2 Calculations

The lifecycle costs necessary to derive the essential LUEC are calculated considering the following starting points:

- For comparison reasons, the EMWG has set the standard currency to January 2007 constant dollars. However due to the origin of data and the nature of this research, all costs are expressed in January 2009 constant euros;
- Total Capital Investment Costs (TCIC), cash flow and overnight construction costs are expressed in January 2009 constant euros;
- Total capital at risk = TCIC;
- The cash flow statement uses annually schedule increments, because of the top-down approach, as proposed by the EMWG;
- All costs are expressed in constant euros without inflation or escalation;
- For comparison purposes, EMWG suggest that taxes should be 5% and 10% for optimal economic and lesser economic environments respectively;
- Contingency is divided in three levels: *base cost*, *schedule* and *performance*;
- Annual energy generation is equally distributed for each operational year;
- Real discount rates are set to 5% and 10% to resemble average costs of capital in optimal and less optimal economic environment to compare them with the scenarios of the previous chapter;
- The plants operational and commercial life is 60 years. An extension of its operating life is possible but not considered for these calculations;
- The average net annual electricity production is 4,730E+09 kWh.

4.2.1 Overnight Construction Costs

To estimate the overnight construction costs (OCC) *accounts 10 through 50* of a Gen IV NPP when little technical details of are known, the top-down estimate approach can be used. The EMWG directs that the top-down approach can be executed by scaling down available cost data – from e.g. a Light Water Reactor (LWR) – with appropriate algorithms to extract the subject estimates (GIF-EMWG, 2007). For the estimation of the LFR, available cost details (by: Roelofs and van Heek, 2011) of the European Pressurized water Reactor (EPR) equipment and components was used. The following generic exponential cost factor was used as proposed by Roelofs and van Heek (2011):

$$C = A + B \times \left(\frac{P_{new}}{P_{ref}}\right)^n$$

Where:

C	= the cost of the subject plant element
A	= a fixed component of the reference plant cost
B	= variable component of the reference plant cost
P	= ratio of subject plant to reference plant component parameter value
n	= exponent that reflects the size benefit of rating for the component

4.2.2 Capitalized Financial Costs

After the OCC are calculated the capitalized financial costs (CFC) (*account 6*) can be derived. The CFC expresses the costs of capital before and during construction. As stated above, no escalation, inflation or particular fees will be included, so this basically leaves the interest during construction (IDC). The IDC is the compound interest over the total OCC during the total construction time. The project schedule, expenditure curves, and cash flow summaries are used to calculate the IDC. It is represented by the following formula:

$$IDC = \sum_{j=1}^{j=J} C_j\left[(1+r)^{t_{op}-j} - 1\right]$$

Where:

IDC	= constant dollar IDC cost
j	= period #
J	= number of periods (years)
C_j	= cash flow for year, reflecting beginning-of-period borrowing
r	= real discount rate expressed annually
t_{op}	= year of commercial operation

4.2.3 Base cost contingency

Contingency on overnight construction costs multiplies *accounts 10 through 50* by the contingency *base costs* percentage. This is 15 % for the FOAK plant and 10% for the NOAK plant.

4.2.4 Schedule cost contingency

Due to the early stage of the generation IV systems, no actual planning contingency can be estimated. Therefore contingency on schedule costs are a factor of schedule uncertainty, incorporated into the IDC. The construction time is estimated to be 8 years for the FOAK plant and 4.75 years for the NOAK plant.

4.2.5 Contingency on performance

The performance of a reactor is measured in its energy production, called the plant's capacity factor (CF). If the plant does not reach its performance goal, i.e. produces less energy than targeted, the lifecycle costs are distributed over less produced energy, so the predicted LUEC will be higher than expected. The CF is set to 85% and to 90% for the FOAK plant and NOAK plant respectively.

Please note that every source of electrical energy has its own capacity factor. For modern nuclear power plants, the CF is about 90% whereas wind energy for example has a typical capacity factor between 20-40% (Wikipedia, 2011).

4.2.6 Total Capital Investment Cost

The Total Capital Investment Cost (TCIC), expressed in constant euros, consists of the overnight construction costs (OCC) *accounts 1 through 5* and the Capitalized Financial Costs (CFC) *account 6* in the following formula:

$$TCIC = OCC + CFC$$

4.2.7 Levelized cost of capital

The nuclear power plant's levelized cost of capital is usually the largest component in the overall cost of electricity. It expresses the TCIC levelized over the plant's total electrical energy output. Given that the plants electric energy output is equally distributed over the number of years of its operational life, the following formula for the Levelized Capital Cost (LCC) can be distracted:

$$LCC = \frac{FCR \times TCIC}{E}$$

Where:

LCC = levelized capital cost in constant euros (€/MWh)
FCR = constant euro fixed charge rate
$TCIC$ = total capital investment cost in constant euros (€)
E = annual electric energy generation for single unit (MWh/ year)

The euro's Fixed Charge Rate (FCR) would normally be used to account for return on capital, depreciation, interim replacements, property tax and income tax effects. However, in this stage of the Generation IV system, cost estimation tax and depreciation considerations are being ignored at present, so the constant euro FCR is calculated as a capital recovery factor, as follows:

$$FCR = \frac{R}{1-(1+R)^{-L_{econ}}}$$

Where:

FCR = constant euro fixed charge rate
R = real discount rate
L_{econ} = economic life of the plant (years), i.e. years of commercial operation

4.2.8 Operations and Maintenance costs

The Operations and Maintenance (O&M) costs *accounts 71 through 79* are the periodic costs other than the fuel related costs. O&M costs start at the moment of commercial operation and continue throughout its entire operating life. An example of typical O&M costs are: labour costs (e.g. operations, maintenance and management staff) salary related costs (e.g. insurance, pensions and benefits) mechanics related costs (e.g. chemicals, lubricants, spare parts) and major capital plant upgrades (e.g. steam generator replacement).

The EMWG makes the distinction between variable and fixed costs. Fixed costs typically relate to the reactor capacity. Costs like most staff costs fall in this category. Variable costs contrarily relate to the electricity production and include, for example, non-fuel consumables. To fit the levelized unit of electricity costs, the O&M costs need to be expressed as constant costs over one year. The O&M costs are the sum of the fixed and variable components divided by the reactor's annual output. The following formula shows how the fixed O&M costs component is expressed:

$$LUECFOM = \frac{FIXOM \times RXCAP \times 10^6}{E}$$

Where:

LUECFOM	= fixed O&M cost component expressed in €/kWe
FIXOM	= fixed O&M component in €/kWe
RXCAP	= net power capacity of the reactor in MWe
E	= electricity production of reactor in kWh/year

The following formula shows how the variable O&M costs component is expressed:

$$LUECVOM = VAROM$$

Where:

LUECVOM	= variable O&M costs component
VAROM	= variable O&M costs component expressed in €/MWh

Capital replacements are not included in the *VAROM*. They are included in the *LCOM* (explained below) by its average levelized value.

Then, the total levelized non-capital replacement O&M cost is the sum of the annual costs of the fixed and variable components, divided by the average annual electricity production. This assumes that each year of operation has the same O&M costs, constant euro costs and annual electricity production. The final levelized O&M costs formula will be:

$$O\&M = \frac{LUECFOM + LUECVOM}{E}$$

Where:

O&M	= constant euro levelized O&M costs
LUECFOM	= fixed O&M cost component
LUECVOM	= variable O&M costs component
E	= average annual electricity production of reactor (kWh/year)

4.2.9 Fuel Cycle Costs

For most generation IV nuclear systems, fuel cycle details are unknown and fuel cycle infrastructure is still non-existing or not yet applied to large scale. The approach used in G4ECONS is the simplified unit cost times the annual mass flow. The overall fuel cycle costs *accounts 81 through 89* are based on the EMWG's assumptions for existing fuel fabrication and spent LWR fuel separation facilities. Each fuel component for both front- and back-end is then derived as follows:

$$F_i = M_i \times P_i$$

Where:

F_i = fuel component cost of step *i*
M_i = quantity of material/service required for step *i*
P_i = price of the material at step *i*

Total levelized fuel cycle costs would be the sum of each step over the entire operational life of the nuclear plant and is derived from the following formula:

$$FUEL = \sum_i \sum_{t=t_0-T_1}^{t=t_0+L+T_2} \frac{F_i(t)}{(1+r)^{(t-t_0)}}$$

Where:

$FUEL$ = total levelized fuel cycle constant euro costs
T_0 = reactor commissioning year
L = reactor lifetime
T_2 = maximum value of lag time (in back-end)
T_1 = maximum value of lead time (in front-end)
r = discount rate
i = fuel cycle step

4.2.10 Decommissioning and Dismantling costs

The decommissioning of nuclear power plant facilities covers the management and actions associated with the end of operation and withdrawal form service. Decommissioning activities start after the end of the technical life if the facility. Usually the costs are covered by funds that are accumulated while the plant is operational (GIF-EMWG, 2007).

The EMWG recommends that an average value should be used if the reactor is other than BWRs or PWRs. In absence of detailed estimates, the constant euro D&D costs should be 33% of the total direct capital costs (*accounts 21 through 29*).
Normally, an external sinking fund is created to accumulate the funds necessary for decommissioning. These D&D funds are assumed to have a discount rate of 5% and 10% real discount rates. The D&D sinking fund is expected to accumulate constant euros over the plant's economic life. The following constant euro sinking fund formula is used to calculate the required annual constant euro payments:

$$LDDP = CDD \times SFF(r_{real}, L_{econ})$$

Where:

LDDP	= the annual constant euro payment made to the sinking fund
CDD	= estimated decommissioning cost, i.e. 33% of the TCIC
SFF(r, L_{econ})	= sinking fund factor at rate r for t years; $\text{SFF}(\text{r}, \text{t}) = \text{r}/[(1+\text{r})^{-t} - 1]$
r_{real}	= real discount rate
L_{econ}	= life of the plant assumed for fund accumulation

Following the approach for the levelized O&M costs, the levelized D&D cost can be expressed as:

$$D\&D = \frac{LDDP}{E}$$

Where:

D&D	= constant euro levelized D&D costs
LDDP	= the annual constant euro payment made to the sinking fund
E	= average annual electricity production of reactor (kWh/year)

4.2.11 Levelized Unit of Electricity Costs

The levelized unit of energy cost (LUEC) that is evaluated includes design, construction, commissioning, operations and maintenance, fuel cycle, and decommissioning costs for the first-of-a-kind (FOAK) through Nth-of-a-kind (NOAK) commercial LFR units. It expresses the costs per unit of electricity produced. This method of expression makes comparison possible with alternatives of electricity production. According to the following formula, the LUEC can be derived as follows:

$$LUEC = \sum_{t=1}^{t=n} \frac{(I_t + FUEL_t + O\&M_t)(1+r)^{-n}}{E_t(1+r)^{-n}}$$

Where:

LUEC	= levelized unit of electricity costs
I_t	= annual capital expenditures period t
$FUEL_t$	= annual fuel expenditures in period t
$O\&M_t$	= annual O&M expenditures
E	= annual production in period t
r	= discount rate
n	= total number of periods

With the assumptions of constant annual expenditures and production, adding the costs of D&D to levelized expenditures: $\sum[I_t(1+r)^{-t} / \sum[E_t(1+r)^{-t}$ to obtain the levelized cost of capital (LCC), the formula becomes:

$$LUEC = LCC + \frac{FUEL + O\&M + D\&D}{E}$$

4.3 Conclusion INEEM

The calculations described above have been carried out from two different perspectives, namely the *FOAK* plant (table 4.1) and the *NOAK* plant (table 4.2). For both plants, two different discount rates were taken into consideration namely: the 5% discount rate and the 10% discount rate, so that it can be compared with the other source of energy generation in the next chapter. These discount rates represent; *an optimal economic environment, low discount rate and quick construction* and; *more risky merchant plant with little economic regulation, higher discount rates and taxes*.

Table 4.1: Results of the INEEM for the *FOAK* LFR power plant expressed in 2009 €/MWh

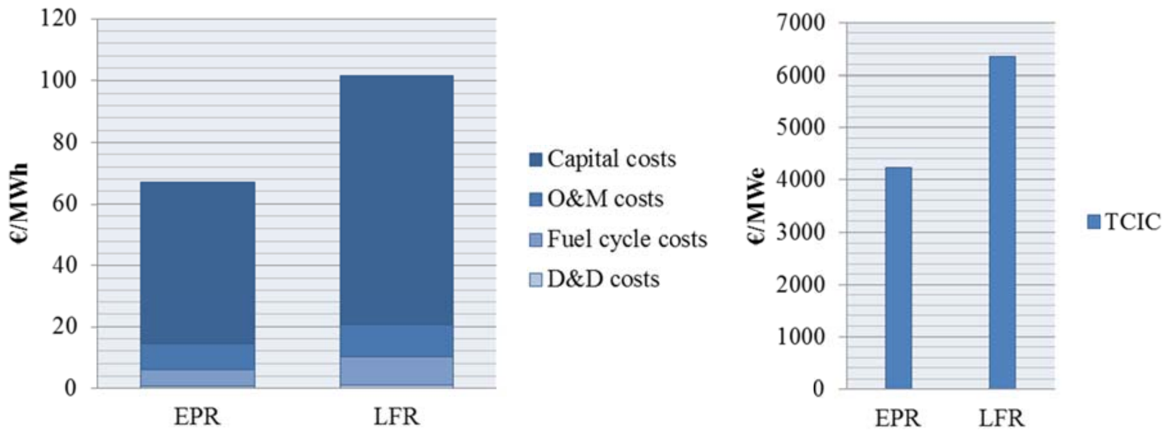
	discount rate 5%	discount rate 10%
Capital costs including financing	42.46	118.23
Operation	7.73	11.6
Fuel cycle front end	3.47	4.56
Fuel cycle back end	1.30	2.30
Fuel cycle total	4.77	6.85
D&D sinking fund	0.023	0.048
Specification TCIC	6,414	8,774
Total LUEC	**62.59**	**146.68**

Table 4.2: Results of the INEEM for the *NOAK* LFR power plant expressed in 2009 €/MWh

	discount rate 5%	discount rate 10%
Capital costs including financing	34.80	87.75
Operation	7.29	10.58
Fuel cycle front end	6.86	12.51
Fuel cycle back end	2.24	4.78
Fuel cycle total	9.10	17.29
D&D sinking fund	0.017	0.04
Specification TCIC	5,549	6,360
Total LUEC	**51.36**	**115.66**

When the costs are compared with the EPR (figure 4.2) that served as the reference plant, it shows that the LFR is over every cost aspect more expensive than the EPR.

Figure 4.2: NOAK LFR cost structure and TCIC in comparison with the reference EPR at 10% discount rates



When compared to the EPR, the LFR does not hold any competitive advantage in financial terms. However, the EPR is based on totally different design principles and it is targeted for maximum power output for the lowest costs at the highest level of safety. Therefore it is acceptable that a waste burning, spent fuel recycling system based on other design principles and for a totally different objective will turn out more costly. In addition, recall that these calculations were based on the technical design like ELSY. Other LFR systems' costs will of course deviate from the ELSY design. Especially the smaller 'battery' and larger 'monolithic' systems as explained in chapter 3 might show different cost structures.

For now these results show its economics and it cannot compete with the economics of an EPR. But before jumping to any conclusions, its overall performance can be compared with an EPR as well i.e. beyond that of economic performance alone. Therewith, other ways of electricity generating exist that the LFR needs to be compared to, to make any judgements of its economic competitiveness in the perspective of the total electricity market, instead of comparing it to the EPR alone. Therefore, the next chapter seeks to provide cost data on alternative systems for electricity generation. The measurement of its performance compared to an EPR is further elaborated in chapter 6.

5 Development of the future electricity market

In the previous chapters, the competences and costs of the LFR are made clear. To further explore the competitive position of the LFR, it is necessary to investigate what the production costs of electricity are for the alternatives and how costs for every alternative will change over time. The costs of electricity production – for both nuclear and other – are subject to a rapidly changing and complex (international) electricity market. Therefore scenario planning is introduced.

This chapter first explains what scenarios consist of and which starting points are considered. The near term costs of electricity production are given followed by the future costs derived from the scenario studies. It follows with the generated scenarios that are applicable on the future of nuclear power plant expansion in the Netherlands. The scenarios that were drafted provide typical power plant characteristics that are essential to measure its performance in the next chapter, the optimum power plant usage.

5.1 Scenario planning

'A scenario contains likeliness of futures to happen. The input for a scenario is often obtained from the past and present trends leading to likely futures, or they are alternatives to existing visions of the future.' (Godet, 2000)

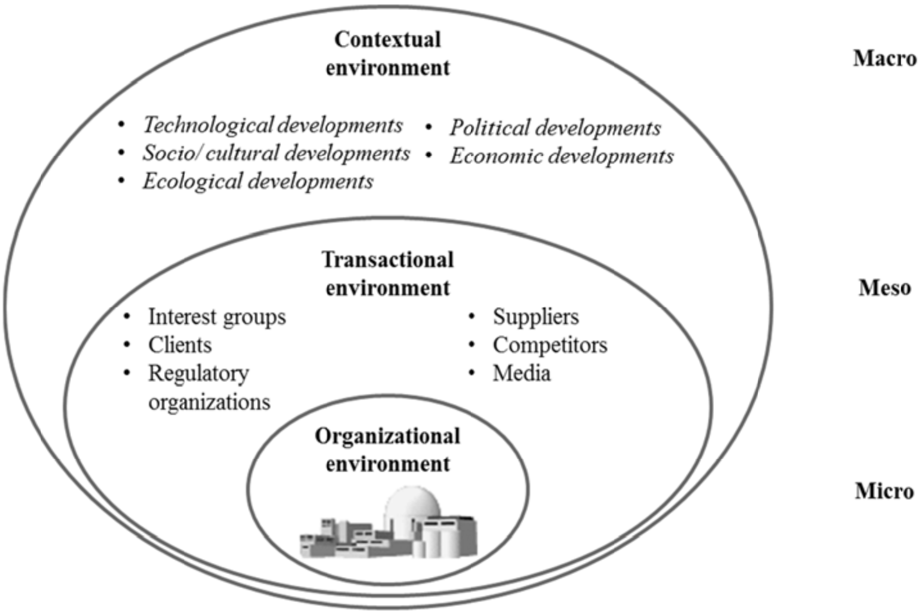
Scenarios are built concerning the so-called environmental forces, as they shape the future state of actions and reactions of the outside world. Scenario planning was first used by military planners in the U.S. in the early '60's. These military planners introduced scenario planning to the corporate world in the '70's where it became a popular tool amongst international business planners and policy makers ever since (GBN, 2004). The method incorporates both quantitative and qualitative input, which increases the search space for possible future stages (Postma & Liebl, 2005). Scenarios therefore are empirically supported and function as a reaction to uncertainties in the market.

5.2 Environmental scenario factors

In literature on scenario business planning (e.g. Huss & Honton, 1987; Postma & Liebl, 2005; GBN, 2004) the following typical environmental forces apply: *social, economic, political, ecological, and technological*. Environmental forces further can generally be applied to three levels of scale, namely *macro, meso* and *micro* as represented in figure 5.1. They may include demographic patterns, social and life style factors, economic conditions, natural resources, ecosystem, political and regulatory forces, technological forces, and international conditions.

These environmental forces are mostly dealt with by reviewing their history, trends, critical uncertainties, and interrelationships among other forces to make the scenarios plausible and avoid "surprises" (Huss & Honton, 1987). These factors will further be identified through the use of – as done earlier – planners and analysts, outside consultants, specialized information services, business models, environmental monitoring and scanning systems, and general literature about the future (e.g. Statistics Netherlands and the International Energy Agency). These data sources help to ensure that the analyses are relevant with respect to the eventual uses of the scenarios. The factors that emphatically apply for new nuclear power plants are those on macro scale (*italicized* in figure 5.1) and as the LFR is in an early stage of development, these are the only factors that can be fairly predicted so that's what this chapter is focussing on. Below, the factors that apply on the electrical energy market and their future expectations are given.

Figure 5.1: Environment of the scenarios around the LFR with the focus on macro level



Adapted from: Notten et al, 2003

5.2.1 Ecological

Most of the greenhouse gas (GHG) produced by humans is caused by the use of energy. In a report of 2009, the International Energy Agency (IEA) states that: '80% of the GHS produced by member countries of the United Nations Framework Convention on Climate Change (UNFCCC) comes from the production, transformation, handling and consumption of energy commodities'. This energy sector is dominated by direct combustion of fossil fuels, leading to this large kind of emissions of CO_2 that form about 80% of the total GHG emissions and about 60% of global emissions (IEA, 2009a). Furthermore, they state in their World Energy Outlook report that; 'in spite of the growth of non-fossil, non-emitting energy (such as nuclear and hydro power), and fossil fuels kept their share of energy supply almost unchanged over the past 35 years'. In 2007, fossil fuels accounted for 82% of the global Total Primary Energy Supply (TPES) where electricity generation uses approximately half of the global TPES (IEA, 2009b).

The international treaty – the UNFCCC that includes among things the Kyoto Protocol - prescribes the duties of member countries according to their responsibility and possibilities to react to the adverse effects of climate change. Amongst these member countries are the members of the Organization of Economic Co-operation and Development (OECD), thus including the Netherlands.

A measure to reduce the emissions from highly emitting GHG power plants is the Emission Trading System (ETS) where major emitting industries have to buy rights for their CO2 emissions. Costs of CO_2 emission-rights in the future are estimated between €50 and €100 per ton of CO_2 equivalent and as a coal-fired station produces around 0.7 tons CO2 /MWh, cost will come between 35€/MWh and 75€/MWh.(GEC,2009).

Furthermore, according to the IEA, the scenario of keeping the earth heated no more than 2 °C must have the largest share of renewables and nuclear power, where current policy scenario has the lowest amount of renewables and nuclear (IEA, 2010).
If these long term objectives will be achieved, the European climate Foundations (ECF) states that at least the investments represented in table 5.1 are necessary. The high capital-intensity is mainly due to renewable energy, with the balance coming from nuclear and fossil plants fitted with high-cost Carbon Capture and Storage (CCS) systems.

Table 5.1: Europe's capital expenditures to 2050 per technology for different scenarios

(*in billion €*)

	Renewable	Fossil	CCS	Nuclear	Total
Baseline	570	435	0	305	1310
80% renewable[1]	1995	30	155	180	2360
60% renewable	1515	45	310	360	2230
40% renewable	810	50	470	540	1870

[1]: remaining part will be half nuclear, half CCS

Source: European Climate Foundation, 2010

Considering the necessary investments in nuclear as presented in table 5.1 above, the amount of new plants will be between 40 and 100 (considering around €5 billion each) for the 80% - and 40% renewable scenario respectively. Technical solutions for the safe storage of spent fuel exist, but the European public remains deeply sceptical about nuclear waste disposal. Only a small number of European countries have been able to select sites as permanent repositories in deep geological formations.

5.2.2 Technological

The scenarios do not depend on future technology breakthroughs nor on electricity imported from neighbouring regions. They are based on technologies that are commercially available or almost available (e.g. CCS). It is reasoned that breakthroughs in technology will only improve the cost or feasibility of the total system. The scenarios concern a mix of low-carbon technologies to avoid over-reliance on a few "silver bullet" technologies; if one technology fails to deliver as expected, the system still works. This allows resource diversification as well as geographical differentiation.
Consequently, the scenarios are not fully optimized for lowest cost: they are not expecting a system based purely on those technologies that are expected to be the cheapest in 2050.
CCS demonstration projects are finished around 2015. Then, this will become an available technology, thus considered competitive in 2040.

Renewable energy sources – wind, solar, hydro, geothermal and modern biomass – will advance technologically and economically. Reliability will increase through the use of storage and smart grids. Costs for biomass and geothermal plants improve by 1% per year. The capital costs for wind onshore and offshore improve with 5% per doubling of cumulative installed capacity. The solar Photovoltaic (PV) cells' learning rate is assumed to be 15% per doubling of installed capacity (ECF, 2010). It will be assumed that the wind capacity will be expanded eight times and solar PV 10 times.

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5.2.3 Societal

European energy demand, as estimated by the IEA, increases with 1.4% in current policy scenario and 0.7% in the 2 °C scenario (IEA, 2010). They further state that energy demand will rise by 40% worldwide, especially in new developing countries (IEA, 2009b).

The Dutch population is expected to grow until 2035 where the population reached 17 million; at this point the growth stabilizes and remains around 17 million inhabitants until at least 2050 (Statistics Netherlands, 2007). The Dutch GDP will grow with 2% year-on-year on average. The European GDP is expected to rise with 1.8% (ECF, 2010). This increase in national and European purchasing power is inherently followed by a rise in electricity demand. Depending on what energy/environment strategy is considered, the future Dutch energy demand ranges from; (1) 128TWh in 2040 with a strong policy on cutting energy needs and improved efficiency, to (2) 149 TWh in 2040 when following current trends (ECN, 2010b). Import and export demand are excluded from this demands.
One of the remarkable contributors to an increasing demand of electricity – concerning technologic advancements – is the electric car. Already, ECN estimated that the number of electric cars will be no less than 2.5 million by 2040 and will grow in numbers since (ECN, 2010a).
Furthermore, in the case of a strong policy on energy demand reduction and improved efficiency (the 128 TWh estimation), one could think of the possibility to introduce district heating, because – as explained in chapter 2 – cities are largely responsible for high concentrations of energy use and a lot of that energy is used for heating.

5.2.4 Economics

The above mentioned ETS will not prove a sufficient measure for the long term climate objectives to be achieved and heavily CO_2 emitting power plants will in the future only be used if fitted with CCS systems. This CCS mostly applies to coal fired plants and on the longer term also for gas fired plants. These systems will enter the market around 1015-2020. Cost estimations for CCS come around €50/ton CO2 which translates into €35 /MWh, which is considerable (GEC, 2009). ECN further adds that: to achieve long term goals, all coal fired plants must be equipped with CCS before 2050 (ECN, 2010c).

The next decades, the Dutch gas stocks will decline and imports of gas will increase. Production of gas from small fields has not significantly increased since the mid-1990s. In the past decade, the Dutch territory is increasingly becoming saturated, both onshore and off; there are scarcely any more large finds, peak gas production has passed and gas reserves are shrinking (EA, 2008). Today's high energy prices mean that the state treasury will see large amounts of funds in the form of natural gas profits, but over the slightly longer term, the stream will dry up due to decreasing gas production.

Besides the increase of capital investments due CCS and the increasing CO_2 emission price, the fossil fuel prices will go up too. Fuel prices are assumed to increase according to the IEA projection in their World Energy Outlook report (2009c). Prices of coal and gas increase by about 1% per year, compounded costs might add up to 60% over the next four decades.

However, with highly increased renewable scenarios, the fossil fuel prices will likely stabilize after 2035, because pressure on these resources decreases and besides, it will slow down the costs of emission rights in the ETS system (IEA, 2009c). In terms, high fossil fuel prices would lower the gap between renewables and fossil fuels, but as shares of renewables increases, the pressure on fossil fuel prices relieves and emission rights will decrease, the gap would be broadened again, thus this creates a sort of paradox. Not to mention, if a high increase in nuclear power occurs, the fossils will be relieved even further. The other way around is that a highly increased share of renewables relieves the available uranium resources so the introduction of commercial fast reactors will likely be postponed further.

Nuclear power utilisation will not increase dramatically and its share in worldwide TPES is actually expected to fall from 14% in 2007 to 11% in 2030 (IEA, 2009c). Therefore, for (European) nuclear reactors, no significant learning curves or marginal will be applied. A mere cost reduction can be applied about 10% for the next 40 years (ECF, 2010).

5.2.5 Political

The future politics will hold the same interests *clean*, *reliable* and *affordable* – as explained in chapter 2 – as these visions are set to 2040 or beyond. The government self already made comments on these visions stating that there already are many uncertainties until 2040 and for the longer term – 2060 – goes that uncertainties increase even more (EAA&I, 2011). As explained throughout chapter 2 and 3, the Dutch government acknowledges the benefits of nuclear energy. Considering this statement the government set up a set of conditions. The following 3 basic scenarios for the future use of nuclear power are set forth by the Dutch government:

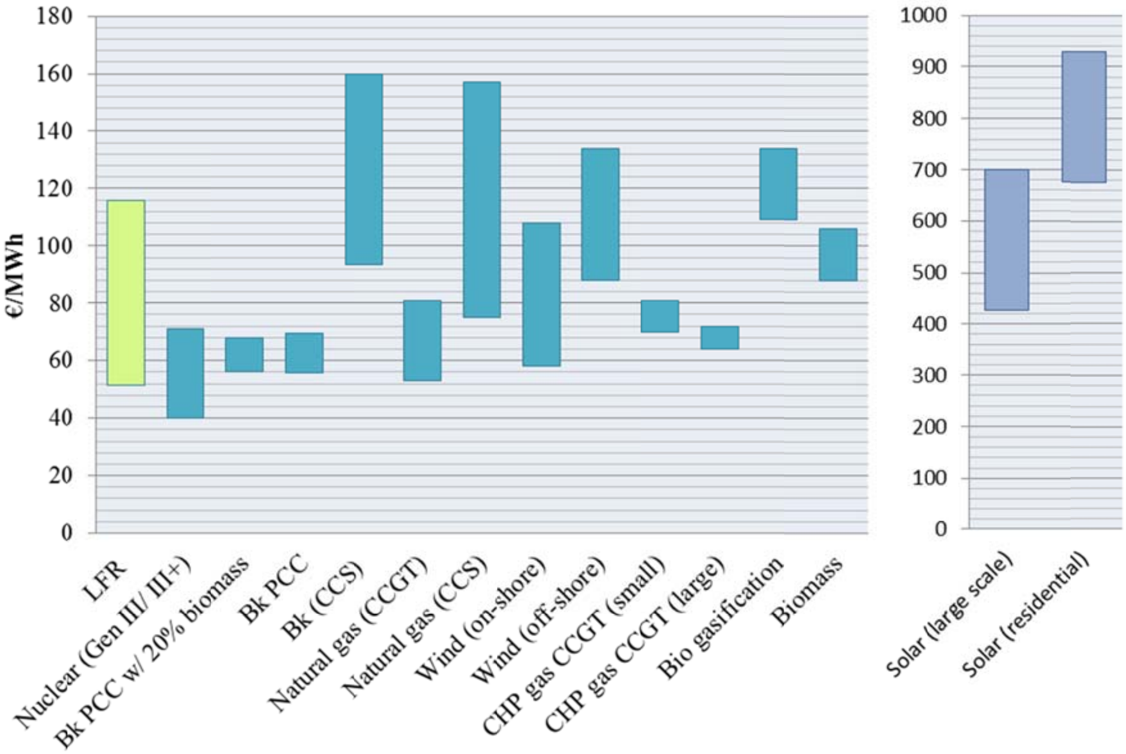
- Scenario 1, variant a: no new nuclear power plants;
- Scenario 1, variant b: no new nuclear power plants, unless inherently safe (i.e. Gen III+);
- Scenario 2: only replace the nuclear power plant of Borssele in 2033 (any Gen III or III+);
- Scenario 3: new nuclear power plants after 2020.

These scenarios provide the basic future government policy decision framework and are therefore taken as point of departure. How these scenarios will be developed and valorised in the future will ultimately affect the Dutch nuclear outcome. But for now, the current established political parties opted for scenario 1b: no new nuclear power plants, unless inherently safe.

5.3 Current market's levelized costs of electricity

To show how these environmental factors influence the costs of electricity production in the future, it is necessary to know what the current costs of producing electricity are. These costs are made readily available by the ECN (2010b) and IEA (2009c) which projected them as from 2015. They are shown in figure 5.2 below.

Figure 5.2: Levelized cost of electricity in the Netherlands as from 2015 (lower bound 5% discount rate; upper bound 10% discount rate)



Where:

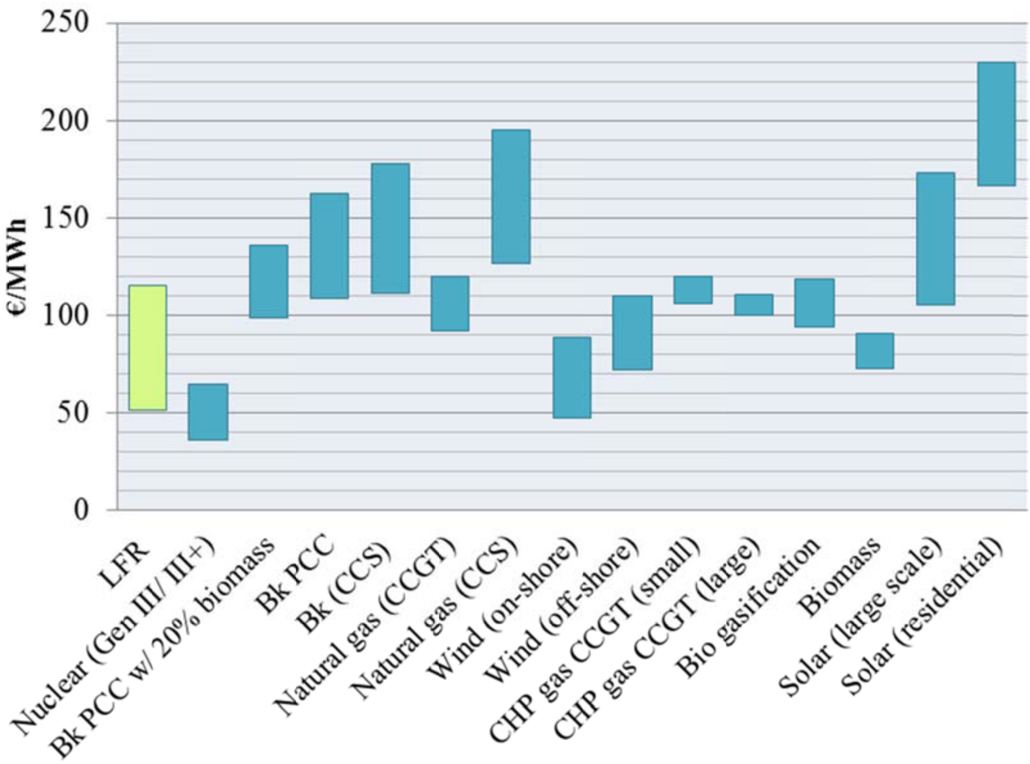
Bk = *Black coal*
PCC = *Pulverised Coal Combustion*
CCS = *Carbon Capture and Storage*
CCGT = *Combined Cycle Gas Turbine*
CHP = *Combined Heat and Power*

Adapted from: ECN, 2010b; except Bk PCC, bk CCS and natural gas CCS, these are adapted from: IEA, 2009c

5.4 Development of the future costs of electricity

Now all environmental factors are examined, the following outline on the future costs of electricity production can be projected on the costs in figure 5.2. The figures stated in the environmental development study are added up to the costs of electricity production represented in figure 5.2, generating the costs of electricity production as from 2050 in figure 5.3 below. The figure clearly shows that, although the LFR system is not economically competitive with the present generation of nuclear reactors, it will be competitive with sources of electricity production. Remarkable is that fossil fuels due to environmental protection measures and increasing fuel prices will be become economically unattractive, placing them out of the market when compared to their clean (nuclear and renewable) counterparts.

Figure 5.3: Levelized cost of electricity in the Netherlands as from 2050 (lower bound 5% discount rate; upper bound 10% discount rate)



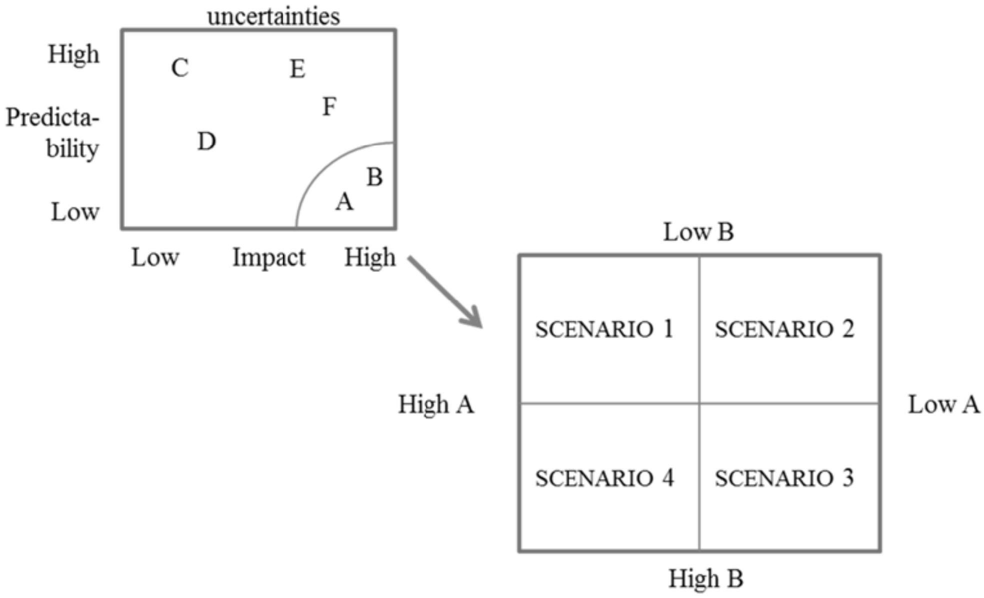
5.5 Future nuclear scenarios

As shown above, nuclear power (Gen III/III+) will clearly remain the most profitable source of electricity production and the production costs of the LFR now seem more competitive compared to other sources than nuclear Gen III/III+. This means that nuclear will still be a sound investment what makes it is crucial to understand how the Dutch nuclear energy program will unravel to see if and how nuclear power can be deployed. Therefore the critical uncertainties need to be elucidated.

Postma and Liebl (2005) state that: one of the earlier steps is to identify the factors that fundamentally determine future developments. These so-called driving forces or causal factors are classified as being *constant*, *predetermined* or *uncertain*. Constant factors are those structural factors that are very unlikely to change (e.g. people's need for electricity and GDP). The predetermined factors' change is largely predictable. For predetermined factors, the outcomes and their probabilities are known, that is, those factors that can be forecasted with reasonable accuracy (e.g. future energy generating costs).
Scenario analyses, however, mainly focus on uncertain factors. The Global Business Network (GBN) prescribes that two or three driving forces should be identified that are most important to the focal issue and most uncertain: '*These driving forces are your "critical uncertainties," and they will be the foundation of your scenario set*.'(GBN, 2004)
Uncertainties refer to those factors of which the outcomes are known, but not yet their coming about. In the scenario processes under consideration, this classification constitutes a crucial step in the scenario process as the uncertainties determine the main differences between the scenarios, while the constant and predetermined elements remain the same for every scenario.

To distinct the future scenarios, Postma and Liebl (2005) suggested the uncertainty matrix as shown in figure 5.4. The uncertainties placed in the bottom right are the critical uncertainties that form the main driving forces of the scenarios.

Figure 5.4: Uncertainty matrix



Adapted from: Postma and Liebl, 2005

At this moment, the government opts for scenario 2: the expansion of nuclear power when inherently safe. However, it is impossible to predict which political parties will be in charge of the Netherlands in 2040, so the policy may shift from one scenario to another the coming decades. This outcome has a very big impact and is in the least predictable, so these scenarios are qualified as the critical uncertainties. This political choice is very much interrelated to the citizens' perception of our future energy security. Chapter 3 revealed a fairly positive attitude towards nuclear power particularly to Gen IV. However, these might shift just like the government's strategy. Therefore, these two uncertainties are qualified as critical uncertainty A, which is placed on the x-axis.
Chapter 3 also brought forth the critical notes on the necessity of improved uranium utilization, the closed fuel cycle and the waste recycling characteristics of future nuclear plants. So at this moment, the necessity remains uncertain and is moreover dependent on national and European policy developments towards nuclear waste management and mitigation. This therefore qualifies as critical uncertainty B, which is placed on the y-axis.

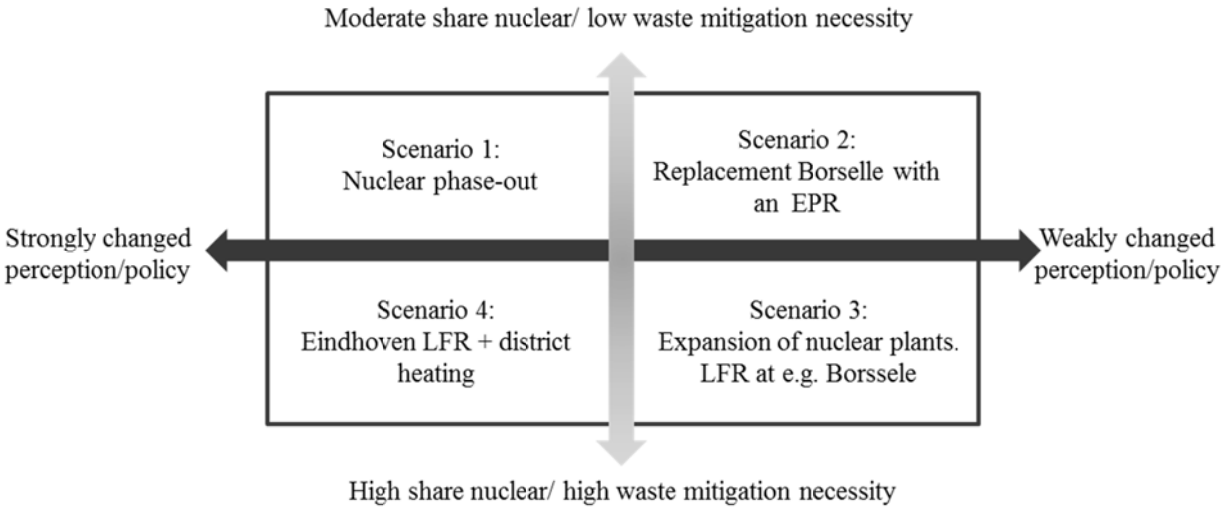
So the critical uncertainties can now be read as:

- A low: business as usual, no turnabouts in policy nor in public perception;
- B low: low interest in Gen IV waste burner because of low share of nuclear power;
- A high: major turnabout towards nuclear power. Either highly turned down or highly encouraged by the public and government
- B high: high interest in Gen IV burner due high expansion of nuclear share;

Based on these uncertainties, the following scenarios have been drafted (figure 5.5):

- Scenario 1: no new nuclear power plants;
- Scenario 2: replacement of Borssele reactor by an EPR only;
- Scenario 3: expansion of nuclear power plants with room for the LFR;
- Scenario 4: LFR with district heating for the city of Eindhoven.

Figure 5.5: The uncertainty matrix that provides the foundation of the scenario set



5.5.1 Scenario 1: nuclear phase-out

One of the most ambitious goals of a clean energy provision system stated by the European Climate Foundation (ECF) (as shown in table 5.1) is to cut GHG-reduction by 80% in 2050 compared to the levels of 1990 (ECF, 2011). That is typically the equivalent of the 80% of total GHG emissions from the production, transformation, handling and consumption of energy commodities. This goal somewhat seems as a drastic objective.
The G8 leaders formed their climate objectives to cut global emissions to at least 50% by 2050. Even fully implemented, it will only be a part of the trajectory to keep the Earth from heating 2 °C. This goal is certainly not out of reach, it only implies that much stronger efforts are needed after 2020, costing considerably more (IEA, 2010). Although these are less ambitious than the goals of the ECF, they are still very doubtful when it comes to practical achievability (IEA, 2010). A Dutch nuclear phase-out program therefore seems unlikely to happen.

5.5.2 Scenario 2: Replacement of the Borssele reactor with an EPR

This scenario is the typical ‘business as usual scenario’. As mentioned before, this scenario is currently happening in the Netherlands. The government pointed out that nuclear power is necessary to guarantee reliability, affordability and to cut GHGs emissions.
The EPR is the most likely candidate for this replacement as EdF and Areva hold strong connections with the current market parties that operate the Borssele reactor.

The EPR as explained will run partly on MOX fuel in the future, increasing the energy efficiency about 30%. When the Dutch government has to make a decision on its waste disposal, the 25-30 tons annually would not be enough to make the LFR necessary. The probable option would likely be long term geological waste disposal.
Further, it is hard to estimate the tax profits for the government, but as the EPR will produce electricity at lower costs than any of the current and future alternatives, the government's action would be to raise a levy so it comes close to renewable energy sources. However if only one new NPP is deployed, this income will not be significant.

5.5.3 Scenario 3: Expansion of nuclear energy and the introduction of the LFR

Considering the general statement throughout the literature that the nuclear energy expansion is necessary to comply with the climate objectives, if (total) reliance on import is not an option, the probability exists that more NPPs will be constructed further than the replacement of the Borssele reactor alone. It is also very likely that this expansion occurs, based on the previously statements that (1) the Netherlands is an interesting place of business and (2) the fact that nuclear power's production costs will remain the cheapest at least throughout this century and (3) that the government is open for issuing new licenses. Therefore foreign investors can be attracted to invest in the Dutch nuclear energy program and sell back the power to their own countries.
The government can incorporate this advantage into their strategies and policies. Therefore it needs to streamline its policy and enable quick decision making, siting and licensing on behalf of the nuclear industry, to make this scenario possible.
Then, in 2050, it can be feasible to deploy the LFR as a waste transmutation system, because the increasing the installed LWR capacity also increases concerns on nuclear waste management. Fully closing the fuel cycle might be feasible, as it takes about 2.5 GW of installed LWR capacity to provide enough spent fuel for the LFR to incinerate.

5.5.4 Scenario 4: Eindhoven LFR with district heating

The final scenario involves an inner-city reactor with district heating. As stated in chapter 2, cities may not be mobilised in time to help fulfilling the future needs of a low-carbon energy provision and only a few cities worldwide started exploring the possibilities. Eindhoven is one of those cities that formulated the ambition to become an energy neutral city – generating as much energy as it consumes –within 2035 not including mobility and in 2045 including mobility (Municipality of Eindhoven, 2011). Some projects already have been started, mostly focussed on the housing market. Besides, the municipality cooperates with students from the University of Technology Eindhoven to expand their knowledge on this sustainable ambition. Student's projects mostly concern energy saving, increasing energy efficiency, improving interchangeability, economics of energy neutral developments and improving cooperation regarding the achievements of these ambitious goals (Kenwib, 2011). Moreover, these initiatives entirely rely on renewable energy sources (e.g. solar pv-cells and biomass)
As shown in figure 5.3, the LFR will be a very competitive alternative to these renewable energy sources. Also as mentioned in chapter 3, small inner-city nuclear reactors are not unfamiliar in the Netherlands and Eindhoven previously had a small nuclear reactor. Plausibly it can be decided to operate a small LFR when market parties are confronted with mandatory participation regarding this energy neutral ambition. This of course will only take place if the local policy and public acceptance allow such development; hence the scenario is placed in the bottom left corner.

5.6 Conclusion future market development

When evaluating the future market developments, some remarkable developments take place. Simply put, fossil fuels costs will go up and renewables costs will go down; the LUECs of these electricity sources are highly influenced by future policy objectives and market developments. It almost comes to a turning point where these sources trade places; except for the fact that renewables still are doubtful regarding their practical feasibility.
Regarding nuclear energy, little changes will occur. As already mentioned in chapter 3, nuclear fuel will remain extensively available and the European share in nuclear hardly increases. Nuclear energy will remain highly competitive in terms of economics for at least this century and because it does, the LFR will not become anywhere near competitive. Nevertheless the LFR can be a competitive alternative for fossil and renewables.

Regarding the nuclear scenarios;
Scenario 1; the government today seems convinced that nuclear energy is necessary, mostly to increase independence and delivery certainty. A strategy to phase-out nuclear power early (before 2050) implies that the government must make a turnabout decision on todays licensed NPPs. This will likely have large financial consequences as utilities will recoup these costs on behalf of the government which are ultimately the Dutch tax payers.

Scenario 2; this scenario is the trend-based scenario and represents the actual ongoing situation in the Netherlands. An EPR when constructed now will at least be operational until 2070. The consequences are neither interesting nor concerning. With only one commercial nuclear reactor at a time this scenario does not contribute significantly to tax yields, stronger independence or stronger international competitive position. It will only reduce GHG emissions if it would actually replace e.g. any coal fired plants, but instead, it is added as surplus power. This scenario will probably not encourage the development of costly waste burners or closed fuel cycles with recycling.

Scenario 3; major expansion of the share of nuclear generated electricity can do the opposite of scenario 2. This means it can contribute significantly to tax yields, stronger independence, stable prices and a stronger international competitive position. It could relieve the dependency on natural gas, especially when this runs out. However if not encouraged strongly by the government, market parties will not bother to make investments.

Scenario 4; the district heat scenario can be a major advancement in energy efficiency, delivery certainty and price stability regarding an energy neutral urban environment. Looked at the energy densities of urban final uses (figure 2.2) a small LFR would be incredibly convenient to overcome some of the hardest challenges of becoming totally energy neutral. The small LFR will totally operate independent of fuel prices and alike. The future local policy however will finally determine the chances for this scenario to happen.

6 Multi attribute decision making tool

Finally, the competitiveness beyond mere economics in comparison with other NPPs is measured. Three out of four scenarios that were drafted in chapter 3, involve nuclear power plant expansion. When the ‘environmental factors’ are discarded from the scenarios, three different NPP configurations – the internal factors – remain. These are the NPP configurations that can be part of the future. The final part of this research is the mutual classification of these NPP configurations with the help of a multi-attribute decision making (MADM) tool. From these NPP configurations, 15 performance attributes were extracted for comparison as shown in table 6.1. These figures were collected through desk research. Henceforth, two methods are introduced to rank these performance attributes by both mathematical relativisation and by stakeholders’ judgements. This is done because the numerical data do not hold any information on the significance of the performance criteria and vice versa, the significance of the criteria does not imply any of the actual figures. To elaborate such MADM tool, two methods are introduced, namely the Grey Relational Analysis (GRA) and the Analytical Hierarchy Process (AHP).
This chapter explains all necessary steps that were made regarding the GRA and AHP methods. Then the results are explained showing which of the three NPPs performs best. Based on this relative performance measurement, a conclusion is derived.

6.1 Grey relational analysis

Grey relational analysis, proposed by Deng in 1982, is part of Grey system theory. This grey system theory includes five major parts: Grey prediction, Grey relational analysis, Grey decision, Grey programming and Grey control (Lee and Lin, 2011). The basic notion of Grey system theory is that; data that is known is called ‘white’. Data that is unknown is called ‘black’. Hence the data that is in between is logically called ‘grey’.
According to literature (e.g. Lee and Lin, 2011; Kung and Wen, 2007; Wei, 2011):
‘GRA is proven to be useful for dealing with problems under discrete, poor, fragmented, incomplete and uncertain data sets and solving their complicated inter-relationships between the multiple factors and variables. In GRA, the global comparison between multiple sets of data is undertaken instead of using local comparison by measuring the distance between two points. It measures the degree of similarity or difference between two sequences or discrete data sets based on the grade of relation.’

It became a popular method to specify the optimal alternative, when usual models like deterministic models and regression analysis fail to assess the multi-attribute, multi-factor relationships and their cross-interaction (Tai et al, in press). The GRA method is now used in a wide area of research in, for example, business performance measuring, construction optimization and product development.

With the LFR still in the design phase, its operational performance figures are based on calculations until demonstration experience is measured in practice. For the EPR goes that its performance data is either factory released, i.e. data is provided by the supplier, or calculated. Furthermore, the performance attributes are expressed in different units of measures, and can only compared relatively as there are no specific benchmarks.
In conclusion, the data sets collected to compare NPP plant attributes are as it seems, dispersed, miscellaneous, uncertain and discrete. Therefore the GRA method appears extremely advantageous.

Table 6.1: nuclear power plant configurations and their performance attributes derived from the scenarios.

Attribute:			EPR	LFR	LFR + DH
A11	Fuel consumption	*mt/yr* [1]	1.35E-04	9.18E-05	9.18E-05
A12	Waste production	*mt/yr*	2,46	1,15	1,15
A13	Radio toxicity	*Svt/TWh* [2]	1.85E+10	2.29E+07	2.29E+07
A21	Load following flexibility	*%*	100	100	100
A22	Cooling water consumption	10^5 m^3/hr [3]	4.914	1.552	1.552
A23	Space requirements	*hectare*	8,571	8,498	8,498
A31	Capital costs	*€/kWh* [4]	52.78	80.93	80.93
A32	O&M costs	*€/kWh*	8.34	10.62	10.62
A33	Fuel cycle costs	*€/kWh*	5.33	9.10	9.10
A34	D&D costs	*€/kWh*	0.030	0.048	0.048
A41	Licensing time	*months*	36	36	48
A42	Licensing uncertainty	*%* [5]	25	25	75
A51	Active/ passive safety	*%* [6]	100	100	100
A52	Public safety hazard	p/km^2 [7]	160	160	2,463
A6	District heat generation	*GWh/yr*	0	0	123

1: metric tonnes per year
2: decay radiation in Sievert per Terawatt-hour
3: 100,000 litres per hour
4: costs A31-A34 are derived from the standard 10% discount rates
5: 25% means low uncertainty, proven concept. 75% means high uncertainty, unusual concept
6: due to very strict safety regulations concerning plant licencing, plants perform equal
7: accommodated population per square kilometre within the vicinity on average

6.1.1 GRA procedure

The main procedure of GRA consists of four steps: Grey relational generating, reference sequence definition, Grey relational coefficient calculation, and Grey relational grade calculation (Lee and Lin, 2011). In Grey relational generating step, GRA firstly translates the performance of all alternatives into comparability sequences. According to these sequences, a reference sequence (ideal target sequence) is defined at reference sequence definition step. Then, the Grey relational coefficient between all comparability sequences and the reference sequence is calculated. Finally, based on these Grey relational coefficients, the Grey relational grade between the reference sequence and every comparability sequences is calculated. If a comparability sequence translated from an alternative has the highest Grey relational grade, that alternative will be the best choice.

6.1.2 Grey relational generating

A MADM problem can be expressed in a matrix format, in which columns indicate attributes considered in a given problem; and in which rows list the competing alternatives. First, let i denote the attributes: $I = \{i_1, i_2, \dots, i_m\}$ for m attributes and let j denote the alternatives $J = \{j_1, j_2, \dots, j_n\}$ for n nuclear power plants.

Hence, the matrix X can be composed from the original data from table 6.1 above:

$$\left(x_{ij}\right)_{m\times n} = \begin{matrix} \\ i_1 \\ \vdots \\ i_m \end{matrix} \begin{matrix} j_1 & \cdots & j_n \\ \left[\begin{matrix} x_{11} \\ \vdots \\ x_{m1} \end{matrix}\right. & \begin{matrix} \cdots \\ \ddots \\ \cdots \end{matrix} & \left.\begin{matrix} x_{1n} \\ \vdots \\ x_{mn} \end{matrix}\right] \end{matrix}$$

"When the units in which performance is measured are different for different attributes, the influence of some attributes may be neglected. This may also happen if some performance attributes have a very large range. In addition, if the goals and directions of these attributes are different, it will cause incorrect results in the analysis." (Lee and Lin, 2011) It is therefore necessary that all performance values for every alternative will be processed into a comparability sequence, thereby transforming matrix $X = \left(x_{ij}\right)_{m\times n}$ into the normalised comparison matrix: $Y\left(y_{ij}\right)_{m\times n}$.

This was done as follows:

In $\left(x_{ij}\right)_{m\times n}$, when the characteristic of the index is 'higher is better', the original sequence, where x_{ij} is the performance value of attribute i of alternative j, can be normalised as follows:

$$y_{ij} = \frac{x_{ij} - Min\{x_{ij}, j = 1,2,\ldots,n\}}{Max\{x_{ij}, j = 1,2,\ldots,n\} - Min\{x_{ij}, j = 1,2,\ldots,n\}}$$

for: $i = 1, 2, \ldots, m; j = 1, 2, \ldots, n$

In $\left(x_{ij}\right)_{m\times n}$, when the characteristic of the index is 'lower is better', the original sequence, where x_{ij} is the performance value of attribute i of alternative j, can be normalised as follows:

$$y_{ij} = \frac{Max\{x_{ij}, j = 1,2,\ldots,n\} - x_{ij}}{Max\{x_{ij}, j = 1,2,\ldots,n\} - Min\{x_{ij}, j = 1,2,\ldots,n\}}$$

for: $i = 1, 2, \ldots, m; j = 1, 2, \ldots, n$

6.1.3 Reference sequence generation

After the Grey relational generating procedure, the performance values are scaled into values in the range [0, 1]. When an attribute i of alternative j, of matrix Y is equal to 1, or nearer to 1 than the value for any other alternative, the performance of alternative j is the best one for the attribute i. Therefore an alternative will be the best choice if all of its performance values are closest to or equal to 1. The optimal attribute values will be used as the reference sequence. The reference sequence is derived from each row's optimum value; $y_{i,opt}$ of that sequence, according to the following formula:

$$y_{i,opt} = max\{y_{ij}, j = 1, 2, \dots, n\}$$

$$z_{ij} = |y_{i,opt} - y_{ij}|$$

for: $i = 1, 2, \dots, n$

Matrix $Z = (z_{ij})_{m \times n}$ is now formed containing all attribute values of each column relatively compared with the optimal reference sequence values.

6.1.4 Grey relational coefficient

The Grey relational coefficient is used for determining how close an attribute *i* of alternative *j* in matrix $Z = (z_{ij})_{m \times n}$ is to the reference sequence $z_{ij,opt}$. The larger the Grey relational coefficient, the closer z_{ij} and reference $z_{ij,opt}$ are. The Grey relational coefficient is calculated, thereby forming the final matrix; the Grey relational efficient matrix $\Xi = (\xi_{ij})_{m \times n}$.

This was done as follows:

$$\xi_{ij} = \frac{\Delta_{min}(z_{ij})_{m \times n} + \rho \times \Delta_{max}(z_{ij})_{m \times n}}{z_{ij} + \rho \times \Delta_{max}(z_{ij})_{m \times n}}$$

for: $i = 1, 2, \dots, m; j = 1, 2, \dots, n$

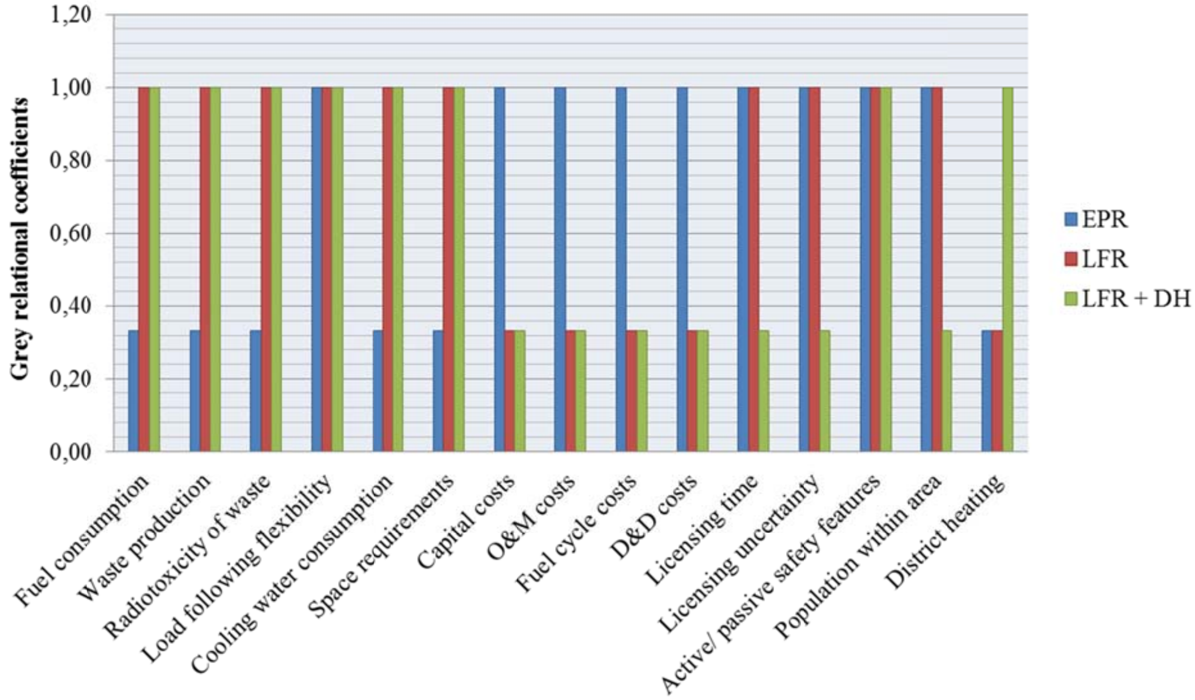
and;

$$\Delta_{max} = max\{\Delta_{ij}, i = 1, 2, \dots, m; j = 1, 2, \dots, n\}$$

$$\Delta_{min} = min\{\Delta_{ij}, i = 1, 2, \dots, m; j = 1, 2, \dots, n\}$$

ξ_{ij} is the Grey relational coefficient of attribute *i* of alternative *j* and indicates its final rank. These final ranks are shown in figure 6.1, a table of the ranks is put in table B.1 in appendix B. ρ is the distinguishing coefficient, $\rho \in [0,1]$. Different distinguishing coefficients can be adopted, but these are usually 0.5.(Lee and Lin, 2011; Xu et al, 2011) Other distinguishing coefficients lead to other differences between z_{ij} and $z_{ij,opt}$, but the rank order will remain the same.

Figure 6.1: Grey relational coefficients



The sum of the Grey relational coefficients for each plant is shown in table 6.2, where goes, the higher the sum, the closer the NPP is to the optimum sequence.

Table 6.2: Grey relational coefficients

	EPR	LFR	LFR + DH
Summed Grey relational coefficients	11.000	11.667	10.333

Clearly the LFR rates the highest followed by the EPR and LFR + DH that rate last. Thus it can be said that the LFR does hold the best overall performance. These Grey relational coefficients however do not hold any factor of importance. Although, the LFR rates highest, another NPP might still be best when considering the significance of these weights. These considerations are taken into account as explained below.

6.1.5 Grey relational grade

The final step is to calculate the Grey relational grade. The Grey relational grade indicates the degree of similarity between the comparability sequence and the reference sequence. The Grey relational grade $\boldsymbol{\Gamma} = \{\gamma_1, \gamma_2, \ldots, \gamma_n\}$ is extracted form multiplying the Grey relational coefficient with a weight attribute $\omega_i = \{\omega_1, \omega_2, \ldots, \omega_n\}$ for each attribute i. The formula by which the Grey relational grade is calculated is formulated as follows:

$$\Gamma_i = \sum_{j=1}^{n} \omega_i \xi_{ij}$$

for: $i = 1, 2, \ldots, n$

As explained above, the reference sequence represents the best performance that could be achieved by any of the sequences in the compared columns. Therefore, if a column of any of the alternatives ranks the highest Grey relational coefficients, it is closest to the reference sequence. That means that the concerning column's sequence is most similar to the reference sequence, and that alternative would be the best choice.
Nonetheless, the Grey relational grade also implies a weight attribute $\omega_i = \{\omega_1, \omega_2, \dots, \omega_n\}$ for each of the attributes i. These weight attributes usually depend on the decision maker's judgements (Lee and Lin, 2011). Though this can be done in a setting where the modeller is the stakeholders or where stakeholders are closely involved in the decision making process, it is less suited for these circumstances. The NPP scenarios involve decision making dependent on plural decision makers' judgements from an extended field of research or sphere of action. Therefore the Analytical Hierarchy Process is used to convert stakeholders' opinions into the subjective weights for the Grey relational grade.

6.2 Analytical Hierarchy Process

As explained in the introduction of this chapter, the numerical data do not hold any information on the significance of the performance criteria. The GRA method can easily reflect the preferential order of different investigated objects according to a certain performance index; however, distinguishing the relative significance among different types of indices is difficult (Xu et al, 2011). In comparison, AHP is a classic method used for evaluating relative significance among indices by opinion and judgement.

The AHP was introduced in the early '70's by Saaty and became popular throughout a wide field of applications since (e.g. Pophali, Chelani, and Dhodapkar, 2011; Xu et al, 2011; Kung and Wen, 2011; Lee and Lin, 2011). AHP is a systematic analysis method for quantitatively treating complex and multi-criteria systems, and can decompose a complex problem into multi-layers and multi-factors, as well as expediently compare and calculate weights (Xu et al, 2011). AHP compares and ranks alternatives according to a set of criteria and sub-criteria that are arranged in a hierarchical structure. Natural language is used to indicate the preference between different criteria and it is translated into numerical preference values (Gomez-Ruiz, 2010).

While the combination of GRA and AHP is quite novel, it has recently been used throughout several fields where data particularly involves qualitative and quantitative information and decision making cannot be undertaken by just relying on either one them (Xu et al, 2011; Kung and Wen, 2011; Pophali, Chelani, and Dhodapkar, 2011). As mentioned before, the NNP development involves a complicated environment where multiple stakeholders are – to a more or lesser extent – involved in the introduction of a new plant to the market. The importance of these stakeholders is described hereafter.

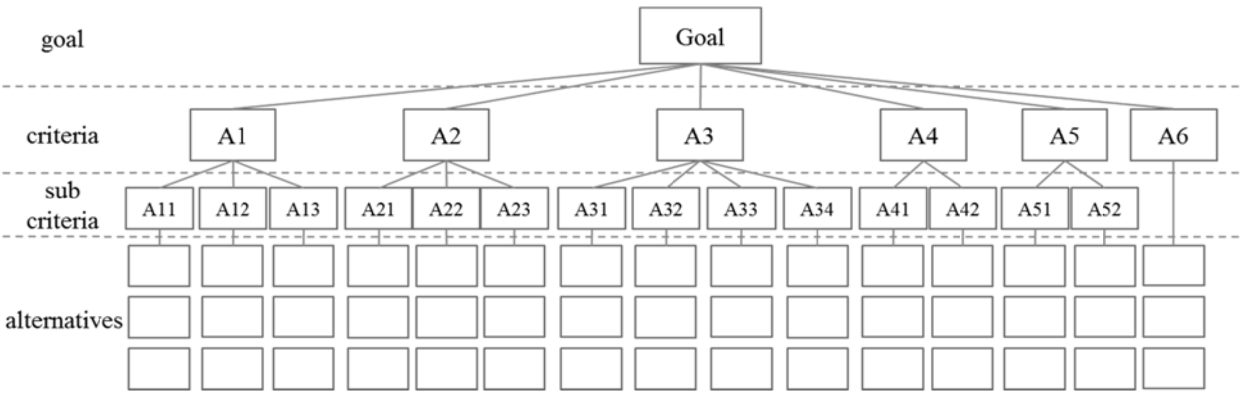
6.2.1 AHP procedure

The AHP procedure consists of the following steps: first, the hierarchal structure needs to be designed which arranges all the criteria and sub-criteria. The criteria are used to label rows and columns of the pairwise matrix, called the comparison matrix. At each level of the hierarchal structure, a pairwise matrix is created according to the corresponding (sub-) criteria. The next step is to fill the intersections between them with a numerical preference value. These preferences values can be obtained by stakeholder judgments by means of a questionnaire. Then, the judgements are checked for consistency. Thereafter, the matrices' eigenvector is calculated by normalising the values of each row. The resulting eigenvector is the principal eigenvector elucidating the relative preferences for each of the alternatives.

6.2.2 Hierarchical structure

The AHP is goal or objective oriented. The purpose of the structure is to disclose the preferential order of attribute significance. This means that the criteria and sub-criteria need to be arranged according to their relevance towards the goal. The main goal – a practical and economical nuclear reactor – is in the first (goal) level. Six major criteria that contribute to the goal were placed in the second (criteria) layer. These major criteria were then divided into 14 sub criteria and placed in the third (sub criteria) layer. The three nuclear power plant configurations that need to be evaluated are in the fourth (alternatives) level. These layers form the hierarchy tree below (figure 6.2). Their unweighed relevance is put in table B.2 in appendix B.

Figure 6.2: Hierarchy tree. The criteria layer and sub criteria layer form the first and second hierarchy index



6.2.3 Pairwise comparison matrix

"The set of all such judgments in making comparisons with respect to a single property or goal can be represented by means of a square matrix in which the set of elements is compared. It is a way of organizing all the judgments with respect to some property to be processed and synthesized along with other matrices of comparisons involved in the decision. Each judgment represents the dominance of an element in the left column of the matrix over an element in the row on top. It reflects the answers to two questions: which of the two elements is more important with respect to a higher level criterion, and how strongly" (Saaty, 2008).

These criterions are used to label rows and columns of the matrix $A = \left(a_{ij}\right)_{m \times m}$, hence called the pairwise comparison matrix. In the pairwise comparison matrix, a_{ij} denotes the importance intensity of criteria i compared to criteria j. The comparison matrix further has a reciprocal property. This means that the importance intensity of i compared to j, has the reciprocal value of j compared to i. The matrix is represented as follows:

$$\left(a_{ij}\right)_{m\times m} = \begin{array}{c} \\ i_1 \\ \vdots \\ i_m \end{array} \begin{array}{c} \begin{array}{ccc} j_1 & \cdots & j_m \end{array} \\ \begin{bmatrix} a_{11} & \cdots & a_{1m} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{mm} \end{bmatrix} \end{array}$$

where: $j = i$: 1 and $a_{ji} = 1/a_{ij}$

Then, for each hierarchy level (i.e. the criteria and sub-criteria level) separate pairwise comparison matrices were composed according to their criteria.

6.2.4 Pairwise comparison

Each criteria and sub-criteria of the first and second hierarchy index respectively needed to be compared in pairs, using individual pairwise questions. The preference values extracted from these questions were collected through individual questionnaires appendix C.

Five different groups of respondents were selected as prominent stakeholders, namely:

- nuclear physicists and researchers;
- utility exploiters not operating a NPP in their energy portfolio;
- nuclear power plant exploiters;
- civil servants of the municipality of Eindhoven;
- citizens of Eindhoven and;
- students from the University of Technology Eindhoven of the major subject Construction Management and Engineering.

They were asked to individually compare each criterion with the next, repeatedly until all criteria were compared to one and another. The respondents had to use the scale in table 6.3 below.

Table 6.3: Pairwise comparison scale

Intensity of importance	Definition	Explanation
1	Equal importance	Two aspects contribute equally to the objective
3	Weak or slight	Experience and judgment slightly favour one aspect over another
5	Moderate importance	Experience and judgment moderately favour one aspect over another
7	Strong importance	Experience and judgment strongly favour one aspect over another
9	Very strong importance	An aspect is favoured very strongly over another

Furthermore it was chosen to perform a rather qualitative than quantitative questionnaire. The number of respondents of each group invited to the questionnaire had a minimum of two and a maximum of five. This was done because of two reasons; (1) there is only one commercial NPP in the Netherlands, what makes it impossible to ask a large population of NPP exploiters, and; (2) the pairwise comparison method demands carful considerations, and expectations were that mostly citizens and students are not able to return perfect consistent questionnaires, making large populations even more unusable.

To join each group's preferences, the geometrical means of each group was taken. Saaty has demonstrated that the geometric mean must be used in judgment groups in order to preserve the reciprocal property (Gomez-Ruiz et al, 2010). From there on, the preference values could be transferred to their corresponding comparison matrices. But before doing so, the responses were checked for consistency.

6.2.5 Deduction of the weights

The priorities that are the final weights of all pairwise matrices are basically the principal eigenvectors of these matrices. To obtain these principal eigenvectors, first the matrices were squared, forming matrix $\bar{A} = (\bar{a}_{ij})_{m \times m}$ as follows:

$$\bar{A} = (\bar{a}_{ij})_{m \times m} = \begin{matrix} & j_1 & \cdots & j_m \\ i_1 & \\ \vdots & \\ i_m & \end{matrix} \begin{bmatrix} a_{11} & \cdots & a_{1m} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{mm} \end{bmatrix} \circ \begin{bmatrix} a_{11} & \cdots & a_{1m} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{mm} \end{bmatrix}$$

To find the eigenvector ω_i, the scores of each row in matrix $\bar{A}$ were summed, obtaining $\bar{\omega}_i$. Then, the sum of each row was divided by the sum of the row totals, like formulated below:

$$\bar{\omega}_i = \sum_{j=1}^{m} \bar{a}_{ij}$$

for: $i = 1,2,\ldots,m$

$$\omega_i = \frac{\bar{\omega}_i}{\sum_{k=1}^{m} \bar{\omega}_k}$$

for: $i = 1,2,\ldots,m$

This process is iterated until the eigenvector remains equal to its predecessor with an accuracy of four decimal places. This normalisation process further implies that: $\sum_{i=1}^{m} \omega_i = 1$

6.2.6 Consistency check

It is important that that the decision maker judgments are consistent and logical. Gomez-Ruiz et al (2010) state as example that: "suppose the decision maker says ''I much prefer A to B and I very much prefer B to C". If he also says ''I much prefer C to A", this last judgment is inconsistent with the previous two and it must be corrected.". Clearly, the consistency of judgments in the decision making is an important factor to be considered carefully. Therefore, the consistency is assessed by the 'consistency check', calculating the consistency ratio (*C.R.*). The consistency ratio is derived a follows:

$$C.R. = \frac{consistency\ index\ (C.I.)}{random\ index(R.I.)}$$

and:

$$C.I. = \frac{\lambda_{max} - m}{m - 1}$$

In the *C.I.*, $\lambda_{\max}$ is described as the largest eigenvalue of matrix $A = \left(a_{ij}\right)_{m \times m}$ of m orders. It can be derived by multiplying the sum of values in the mth column by the eigenvectors of the mth row of matrix *A*. As follows:

$$A_i = \sum_{i=1}^{m} a_{ij}$$

for: $j = 1,2,\ldots,m$

$$\lambda_{max} = \sum_{i=1}^{m} A_i \omega_i$$

for: $j = 1,2,\ldots,m$

The *R.I.* is obtained from 500 positive reciprocal matrices randomly created by Saaty (Saaty, 2008). The *R.I.* is presented in table 6.4 below, where m denotes the number of orders of the reciprocal comparison matrix. The hierarchy in question consists of three-, four- and six-attribute matrices, thus the *R.I.* varies dependent of these numbers. Because of the reciprocal property of the matrices, the two attribute matrices are not mentioned, as they essentially are consistent.

Table 6.4: values of the random index.

m	3	4	6
R.I.	0.58	0.9	1.24

If the *C.R.* is small, i.e. < 10% or less, the eigenvector ω_i associated to the largest eigenvalue of matrix *A* can be accepted. Thus the *C.R.* must be smaller than 0.1. When the C.R. is larger than 0.1, the criteria need to be adjusted.

The adjustments were made, based on the relation between the comparison matrix and its eigenvalue. The largest eigenvalue of a perfect consistent matrix must be equal to the number of criteria (Gomez-Ruiz, 2010). This relation can be described as follows;

$$n\lambda_{max} - n = \sum_{\substack{ij=1 \\ i \neq j}}^{n} \left(\varepsilon_{ij} + \varepsilon_{ij}^{-1}\right)$$

Where $\varepsilon_{ij} = a_{ij} \times \frac{w_j}{w_i}$

If ε_{ij} is the farthest from one, then more perturbation exists in a_{ij} (Gomez-Ruiz, 2010). This criterion is altered so that the consistency eventually will decline below the 10% acceptance boundary.

6.2.7 Questionnaire results

After the questionnaires' consistency is accepted, the results can be processed into figures 6.3 and 6.4. None of the civil servants of the municipality of Eindhoven did respond unfortunately. Of the other groups, five nuclear scientists replied, two utility exploiters, two NPP exploiters, five citizens of Eindhoven and five students of the University of Technology Eindhoven.

The first hierarchy in figure 6.3 shows the individual group's rating of the importance of the first criteria level. The total shows the geometric mean of all groups. The columns in the graph show the added criteria ratings so that their mutual relations are revealed.

Figure 6.3: Questionnaire ratings of the criteria (first hierarchy level)

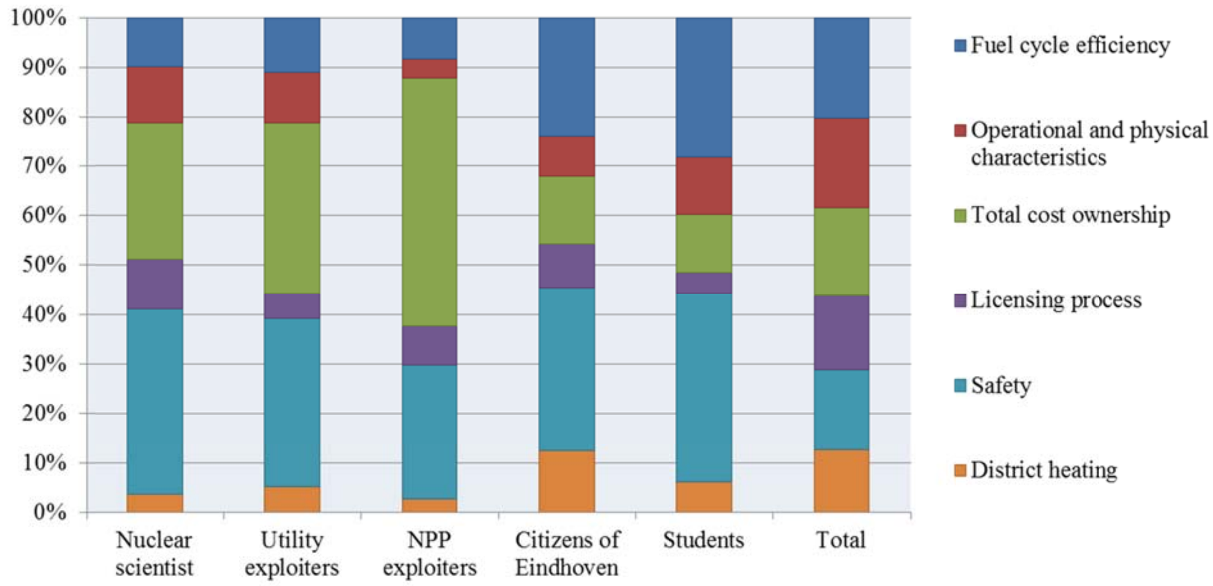
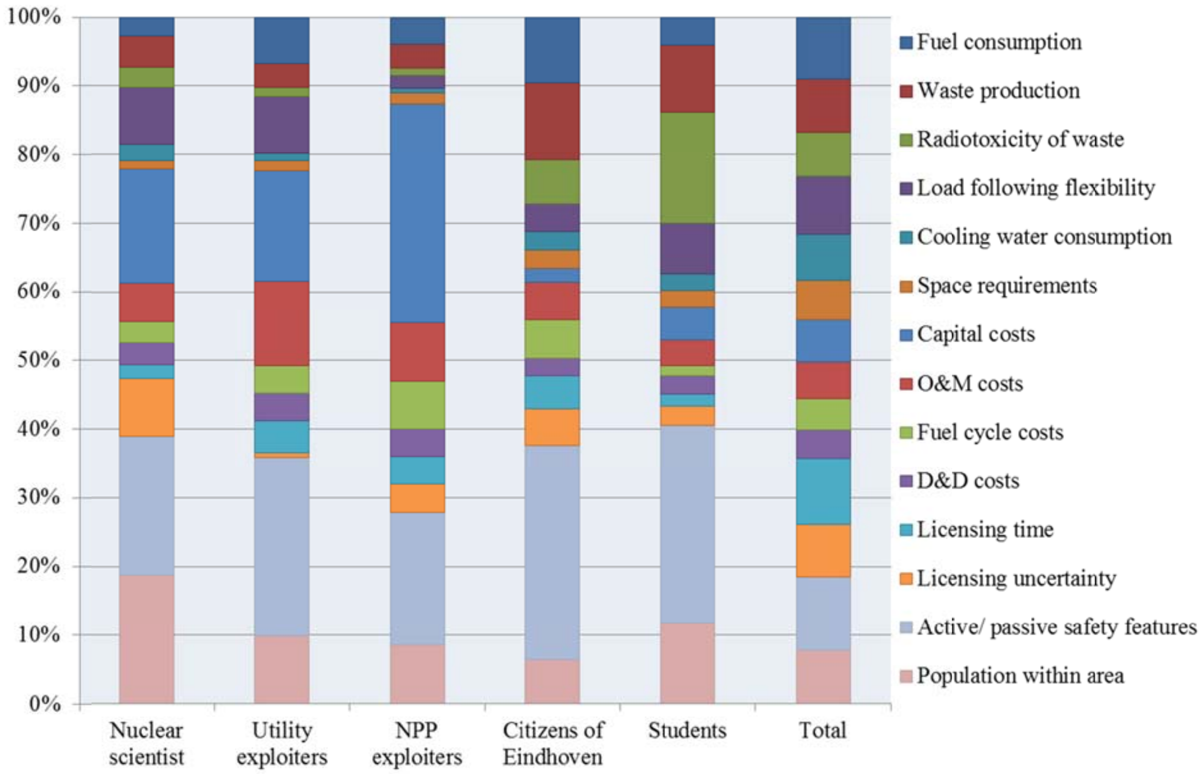


Figure 6.3 shows that total costs ownership is rated the highest in the groups of nuclear scientists, utility exploiters and NPP exploiters, hence denominated as 'the industry'.
It is remarkable that the industry rated fuel cycle efficiency lower than non-industry. This clearly relates to their knowledge about once through and closed fuel cycles and the related available uranium resources and waste management. As explained in chapter 3, there is a low urge to fully recycle fuel.
Regarding fuel cycle efficiency, the NPP exploiters deviate from the utility exploiters as in non-nuclear industry, as fossil fuel are the most important costs factor as uranium is far less sensitive to availability and costs fluctuations.
Overall, safety is rated high through all groups, although the lowest by NPP exploiters. It can be explained that NPP exploiters do not determine safety regulations, so for them, complying with already strict regulations and permits is sufficient as increasing safety beyond regulations will not increase yields.

District heating (DH) finally is rated higher with the non-industry. This can be explained probably because the citizens can imagine their final consumption savings. Students see benefits of using all the energy involved within a NPP and not disposing waste heat as education currently motivates students to think in sustainable solutions. The NPP exploiters have the least interest in DH because this is not within their commercial scope, unlike with utility exploiters who nowadays explore more of these initiatives.

By multiplying the importance criteria of the first hierarchy level with the criteria in the second level, the ratings of the sub-criteria level can be derived.
The second hierarchy in figure 6.4 shows the individual group's rating of the importance of the sub criteria. The total shows the geometric mean of all groups.

Figure 6.4: Questionnaire ratings of the sub criteria (second hierarchy level)



The fuel cycle sub criteria ratings tell us that non-industry finds the waste production and radio toxicity more important than the industry. Again this can be explained by their lack of knowledge regarding fuel cycles compared to the industry and the public sentiments concerning waste production and disposal. This confirms the statements of chapter 3 that the public will choose for the safest, least polluting reactor possible. The difference in fuel consumption between nuclear and non-nuclear industry is, as explained above, associated to the predominant fossil fuel price. The difference in operational flexibility rating between nuclear and non-nuclear industry might be associated to their experience with flexibility of gas turbines that can follow load more easily.
Regarding the costs structure of NPPs, the non-industry could not make clear distinctions concerning the importance of one characteristic over the other. The nuclear industry rates capital investment costs as most important because with NPPs, upfront capital investment

costs are the predominant costs factors contrary to fossil fuel related power plants, where fuel is the predominant costs factor.
Further it can be noticed that the non-nuclear industry have more concerns for licensing time than uncertainty, which confirms to the statement that fossil fuel power plants are distinguished by a shorter time-to-market. The non-industry could not make clear distinctions concerning licencing time or uncertainty.
Finally all groups place significant higher ratings to the passive and active safety features of a plant in relation to the population within the vicinity. This proves quite favourable for the district heating scenario. Only nuclear scientists rated the importance of both safety aspects nearly equal. This can probably be associated to design aspects as a NPP in a densely populated area require a significant research and design effort.

6.2.8 Final ratings

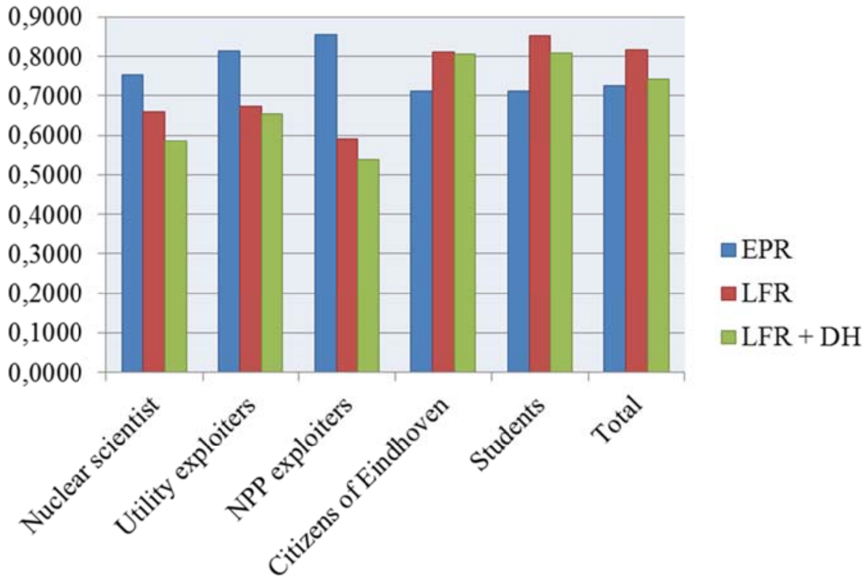
With the calculated Grey relational coefficients and with the results of the questionnaire, each groups' most preferred NPP plant can be distinguished. This 'ideal' NPP is expressed by the highest Grey relational grade. Recall that the formula for the Grey relational grade was:

$$\Gamma_i = \sum_{j=1}^{n} \omega_i \xi_{ij}$$

for: $i = 1, 2, \ldots, n$

At this point, the formula can now be complemented with the weights obtained from the analytical hierarchy process, ultimately demonstrating the attributes preference order. The final grades (table B.3 in appendix B) that were generated are represented in figure 6.4 below.

Figure 6.5: Grey relational grades. These grades express each group ultimate preferred NPP



6.3 Conclusion MADM

The MADM tool has proven to be useful in the assessment of the advantages and disadvantages of the three compared NPPs. The results clearly show that the LFR has the highest Grey relational coefficient which indicates a slightly higher overall performance. However, these figures do not represent any useful information regarding the significance of this performance. Therefore the AHP was introduced which resulted in the final ratings of competitive (dis)advantages. The AHP comparison proved any of the expectations to be true. The stakeholders that decide the significance of performance attributes clearly indicated cost as predominant factor. This revealed that the EPR characteristics are the most valued competitive advantages which can simply be reduced to the excelling costs aspects. The expectations that students and citizens would value the sustainable advantages higher are also confirmed. This leads to the suspicion that district heating might be acceptable for them in the future. None of the civil servants of the municipality of Eindhoven did respond unfortunately. This was rather crucial to get an indication for district heat preferences. Further conclusions on the MADM tool are explained in the next chapter where the research question is answered.

7 Conclusion

The aim of this research was to tell if a more sustainable nuclear reactor can be part of our future energy mix.
This objective is can be seen from a twofold perspective, namely:

1. can offer a sustainable solution to future energy challenges and;
2. will the LFR be a competitive option on tomorrow's energy market.

And to answer the main research question:
'Can the LFR be more advantageous than current market alternatives in terms of economics and performance'

The following sub-sections will answer the main question and explain the general conclusion and achievements of this research.

Does the LFR have practical benefits for the future's energy mix

The LFR certainly has benefits for the futures energy mix when considering its waste burning capability and fuel utilization. In addition, nuclear power plants are one of the few remaining type of power plants that can continue to deliver electricity in environmental friendly and reliable ways. The burning competences of spent fuel will are very practical, but probably only if on the short term, the share of NPPs namely LWRs increases in the Netherlands.

The current government stated that the security of energy supply would remain a policy spearhead, along with efforts to cut carbon dioxide emissions in line with European targets. Hence "the government will be open to issuing permits for new nuclear power plants."
The coalition agreement of the incoming government then says: "Regarding energy supply, the Netherlands must become less reliant on other countries, high prices and polluting fuels"

The LFR therefore is highly practical and in combination with breeders, the application of nuclear fast reactors in the Netherlands can continue for centuries ensuring delivery certainty, independence and low costs for the very long term. On the short term however, the LFR does not hold any competitive advantages for as long as fossil fuels, uranium and CO_2 penalties remain cheap. The urge to invest in clean, abundant and independent energy resources today is still not drastic enough to make the step towards closed fuel cycles.

Does the LFR have economic advantages in terms of electrical energy production costs and capital risks over the alternatives

Another spearhead of the government's policy is that 'energy security must be increased and more attention must be paid to the potential profitability of energy'. In terms of security, the LFR will perform excellent, however, in terms of profitability, the current and future Gen III/III+ LWR reactors will prevail. In addition, the capital at risk is far higher with the current generation NPPs.

The investigated LFR is not competitive compared to an EPR, nor is the closed fuel cycle with full recycling compared to the once through cycle at this moment. As the scenario study has shown, the share of NPPs will not increase drastically next decades. The urge to make the transition to closed fuel cycles with fully plutonium and MA recycling will probably not be made in the 21st century as costs of uranium will not likely exceed the US\$360/kg. The additional capital investment costs of a FR can already be justified from US$140/kg uranium, but only when capital costs are equal to that of a LWR employing a once through cycle. Market parties deciding to build a new NPP will therefore not likely opt for the LFR until the price of uranium comes anywhere close to these break even points.

Nonetheless, it was shown that the LFR, including the high front- and back end costs of its nuclear fuel cycle, will ultimately be competitive with alternatives of electricity generation, in particular with renewables. If then, the LFR will benefit from its competitive advantages over these renewables in terms of reliability, compact size and high energy generation density and high capacity factor what make it a practically more feasible option.

What is the supply and demand structure of the electricity market, and how will this likely evolve

At the moment, the Dutch energy provision is incredibly dependent on its natural gas resources that – on the short term – cause volatile market developments because of the high export standards and pricing and – on the long term – will become an evident difficulty when depletion comes closer.
The current energy policy is focussed on a safe, reliable, flexible, international, independent and affordable, low CO_2 energy management. The main objective is to boost the economy. To achieve these ambitions, especially the competitive, secure and sustainable related ambitions, the government plans closer international cooperation.
As far as the policy considers, the four major options stated in the very introduction of this thesis, are still relevant and none of these options can be abandoned at this preliminary stage.
Power plants that utilize fossil fuel combustion will be heavily affected by this policy as the ETS and or CCS systems will make costs of generation unattractive. Not to mention that natural gas fired plant in particular will suffer from depletion. The expectations are that by the midst of this century, the Dutch will become importer of natural gas instead of net exporter as today. It is therefore really a matter of time, before reliance and competitiveness of fossil fuel fired power plants will become a minority in the total Dutch electrical energy provision.

Regarding the demand structure, the future tells that it will increase ever due to an increasing population, technology advancements and a strong GDP. The European countries that can now be provided with electricity from the Netherlands will stress this demand even further.

How does the LFR perform compared to existing NPPs

The MADM tool has proven to be useful in the assessment of the advantages and disadvantages of the three compared NPPs. The results clearly show that the LFR has the highest Grey relational grade which indicates a slightly higher overall performance. This is mainly due its fuel and waste handling characteristics. When the stakeholders' opinions are taken into consideration, the best performance becomes twofold. Namely the industry rates the EPR as best performing, whilst the non-industry rates the LFR as best performing. This conclusion shows that the non-industry – confirming to the general survey that was held nationwide – perceives the waste-handling performance of a LFR as the key performance indicator. On the contrary, the industry pointed out capital investment costs as the major key performance indicator.

It is the industry that ultimately judges which NPP is economically attractive and therefore which power plant will be deployed in the future. Thus, with costs rated as the major driving forces, the LFRs performance will not be competitive enough to become feasible on the short term.

What do stakeholders prefer regarding NPP performance

It was shown that total costs ownership is rated the highest in the groups of nuclear scientists, utility exploiters and NPP exploiters. This confirms to the statement made in in the introduction that the market entry of new systems predominately is logically a matter of costs.

The industry's knowledge about once through and closed fuel cycles and the related available uranium resources and waste management seemingly made them rate the fuel cycle efficiency lower than non-industry. Please note that efficiency in the questionnaire was related to the efficiency of the utilization of uranium, whereas the results in chapter 3 showed that the open fuel cycle is more efficient, at least regarding its economics. Either open or closed, the nuclear industry rated the fuel cycle efficiency more important at the back-end.
Regarding fuel cycle efficiency, the NPP exploiters deviate from the utility exploiters as in non-nuclear industry, as fossil fuel are the most important costs factor as uranium is far less sensitive to availability and costs fluctuations. This insensitivity is a major benefit to the reliability, energy security and stable cost of delivery.

Overall, safety is rated high through all groups, although the lowest by NPP exploiters. It can be explained that NPP exploiters do not determine safety regulations, so for them, complying with already strict regulations and permits is sufficient as increasing safety beyond regulations will not increase yields.
District heating (DH) finally is rated higher with the non-industry. This can be explained probably because the citizens can imagine their final consumption savings. Students see benefits of using all the energy involved within a NPP and not disposing waste heat as education currently motivates students to think in terms of sustainability. The NPP exploiters have the least interest in DH because this is not within their commercial scope, unlike with utility exploiters who nowadays explore more of these initiatives.

How can the LFR be deployed in the future, regarding which product-market combination

All in all, the window of opportunity for the expansion of nuclear power is significantly stretched. Public and private interests in this technology are high as it ultimately confirms to the clean, affordable and reliable source of energy. The extreme high power output and high quality of the electricity grid throughout the Netherlands offers great import independence as well as it reinforces the Dutch position and competitiveness on the international energy market. In spite of Germany's nuclear exit program, EU countries like the UK, Sweden, France and Finland also acknowledge the use of nuclear power and accompany the Netherlands with their policies. This can lead to joint research efforts and shared nuclear energy related facilities in the future.

The available amount of uranium resources will not likely put pressure on the development and deployment of fast reactors. It cannot be stated how rapid the price of uranium will go up and at least for the 21st century, LWR reactors can be operated without the need for ‘breeders’. However, the interest in fast reactors deployed as ‘burners’ remains.

Geological disposal is technically feasible but execution is not yet demonstrated or certain. Not every European nation has pointed out, or is capable with long-term geological storage. So to stimulate a cost-effective European approach, preferably if possible in the context of a European market, those countries that have opted for nuclear energy have to consider seeking solutions for end-storage of high-level waste (HLW).
The Dutch government needs to decide on long-term waste deposit siting by 2016. The LFR therefore appears a profound solution to mitigate the volume of spent fuel and HLW when the Dutch will expand their nuclear capacity. Even when and if the Dutch will totally abandon their nuclear energy program, the European market will still be open for the technological feasible LFR. Especially if the costs of long term geological disposal will increase or more likely, if public acceptance of long term HLW disposal in geological layers will not be accepted. The LFR needs to be compared with other burners first to make a sound statement on the competitiveness as burner. For now, it is shown that a burner reactor will be more acceptable by the public in comparison to direct geological disposal.

Finally, regarding the LFR combined with district heating, some critical notes have to be placed regarding the approach of this research, because the original idea was to have the very small (<50MW), self-sustainable long life ‘battery’ reactor as an inner-city option. As the technical data of this LFR option was not available or at least not from any reliable source, the comparison in chapter 6 was based on the industrial size 600MW option. The actual characteristics of the battery options will vary as this basically involves different design principles.

Nevertheless based on current commercial advertising on fixed electricity prices (e.g. NUON, 2011; Nederlandse Energie Maatschappij, 2011) it can be notified that both business and private persons are interested in fixed electricity prices over longer periods of time. As a small battery option will provide 15 to 30 years (without refuelling) a fixed (cheap) price of electricity, it might be a viable idea and further research into the battery might repay itself. In addition, the small nuclear reactor deployment in inner-city areas are more accepted as already proven by the HOR and ATHENE reactor that have both operated or still do in a densely populated area. One critical note must be placed namely that current (large monolithic type) NPP operators do not have any interest in the small scale exploitation of district heating. The battery option solely for electricity generation can on the other hand be more competitive.

7.1 Discussion

The first goal was to provide a clear understanding on today’s energy needs, energy policy and energy provision in relation to our society. The question rose if cities will be able to cope with the energy transition. This is a very interesting question and further research will be needed on city scale as this research effort proceeded mostly on (supra) national scale as this is the foremost environment of the (nuclear) energy industry.

The second goal was to show the competences and goals of revolutionary nuclear reactor designs. Only the potential of fast reactors in general was investigated and the research proceeded with taking only one very particular Gen IV reactor into consideration.
The competitiveness of other Gen IV reactors remains therefore unknown and will be of interest in further research.

The third goal was to provide insight in the costs structure of this particular LFR system so it could be compared with the market supply systems. The costs input for the LFR came from preliminary designs as the input form the EPR mostly came from the supplier and is therefore always more optimistic than in reality. This unfairness was straightened out by running the EPR data through the same G4econs model as the LFR was calculated with. The fact still remains that the EPR is already under construction today and comparison will be more reliable when the LFR becomes in the same advanced stadium.

The fourth goal was to present a projection of the future energy market system. The investigated LFR however is not operational before 2040 whilst in this future projection, it was compared with LWRs and other sources of electricity production that already experienced decades of operation. Therefore, when the LFR becomes in a further design phase where more detailed costs estimations can be made, it can be recommended to review its cost competitiveness.

Furthermore, the future regarding new nuclear energy deployment was represented by four plausible scenarios that are based on the most critical uncertainties. Regarding scenarios 3 and 4, some crucial research still needs to be performed.
In scenario 3, it could not be determined at this moment, how many LWRs it would require to make the LFR a logical and viable option as incinerator.
In scenario 4, the battery option's technical data was not yet available; therefore the industrial size LFR was taken as point of departure for comparison in chapter 6. Once the battery option is available, any conclusions in behalf of the battery need to be revised.

The final goal was to deliver a tool by which mutual NPP performance can be measured. The purpose of this tool was to assess the advantages and disadvantages of the LFR's performance compared to a current established NPP. For now, the LFR has been compared with an EPR. As explained earlier, the EPR is developed with different objectives in mind. Comparison between these two might not reveal as much information as when the tool would be used to compare NPPs of the same technical scope and objective. Consequently a logically step would be to use the MADM tool to compare future Gen IV systems or even more particular Gen IV lead-cooled systems when more of these systems' technical data becomes available.

7.2 Recommendations

Nuclear is a mature technology and no specific incentives are needed. It could easily be the backbone of the Dutch national energy provision, once gas production is near exhaustion. The Dutch government then needs to seek ways for skimming proportional profits so that all the Dutch share benefits. However, for nuclear energy to be really cost effective and to really be a source of energy future generations can rely on, the Dutch government needs to formulate clear policies and probably have to cooperate with both utility companies as civilians in order to match interests.

Streamlining of regulatory processes and standardisation will enable both utilities and government (and civilians indirectly) to maximum benefit from nuclear energy. High upfront investment costs make the issue of regulatory uncertainty crucial for market parties and their investments in the Netherlands as a place of business. This issue has to be considered by governments as in the end nuclear energy will remain a public-private issue. Without a clear position in a government 'vision' on the fuel mix, investments will not be made.

In future scenarios, whether the share of renewables is high or low, nuclear power remains a reliable and competitive source of electricity. The only reasonable strategy is to keep a mix of energy products as long fossil fuel remains dominant. The paradoxes revealed in chapter 5 showed that when one of the technologies the mix is heavily encouraged solely, it will most likely prevent major breakthroughs of others.

The government has an important and decisive role in formulating a policy framework for radioactive waste disposal as it cannot be expected that these issues will be solved by a private party. This framework has to involve siting issues for storage and long term disposal, as well as siting issues for fuel cycle reprocessing and recycling infrastructure. Because currently no infrastructure or facilities for fully closed fuel cycles with recycling exists in Netherlands, major regulations and licensing issues need to be resolved first before private market parties can be attracted. High upfront costs of investment in these facilities again make the issue of regulatory uncertainty crucial; as long as this is not clear, no investor will risk their money on a LFR waste burner or on reprocessing infrastructure.
The Dutch government might have to consider long-term options for high radio-active waste in cooperation with neighbouring countries as for now; every EU member state has to deal with the waste issues themselves. Logically, those countries that benefit from security of supply and lower prices because of cross border markets could look for cooperation in waste management and transmutation as well.

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Appendix A: Code of Accounts

The EMWG Code of Accounts (COA) consists among others of the following accounts:

The first digit groups costs by type:

10 – Capitalized Pre-Construction Costs	CPC
20 – Capitalized Direct Costs	CDC
30 – Capitalized Indirect Services Costs	CIC
40 – Capitalized Owner"s Costs	COC
50 – Capitalized Supplementary Costs	CSC
60 – Capitalized Financial Costs	CFC
70 – Annualized O&M Cost	AOC
80 – Annualized Fuel Cost	ASC
90 – Annualized Financial Cost	AFC

The second digit identifies costs summarized by the first digit:

10 – Capitalized Pre-Construction Costs (CPC)
11 – Land and Land Rights
12 – Site Permits
13 – Plant Licensing
14 – Plant Permits
15 – Plant Studies
16 – Plant Reports
17 – Other Pre-Construction Costs
19 – Contingency on Pre-Construction Costs

20 – Capitalized Direct Costs (CDC)
21 – Structures and Improvements
22 – Reactor Equipment
23 – Turbine Generator Equipment
24 – Electrical Equipment
25 – Heat Rejection System
26 – Miscellaneous Equipment
27 – Special Materials
28 – Simulator
29 – Contingency on Direct Costs

Accounts 10 + 20 = **Direct Costs** (DCC)

30 – Capitalized Indirect Services Cost (CIC)
31-34 Field Indirect Services Costs (FIC)
31 – Field Indirect Costs
32 – Construction Supervision
33 – Commissioning and Startup Costs
34 – Demonstration Test Run

Accounts 10-34 = **Total Field Cost** (TFC)

35-39 Field Management Services Cost (FMC)
35 – Design Services Offsite

36 – PM/CM Services Offsite
37 – Design Services Onsite
38 – PM/CM Services Onsite
39 – Contingency on Indirect Services Cost

Accounts 10 + 20 + 30 = **Base Construction Cost** (BCC)

40 – Capitalized Owner‟s Cost (COC)
41 – Staff Recruitment and Training
42 – Staff Housing
43 – Staff Salary-Related Costs
44 – Other Owner‟s Costs
49 – Contingency on Owner‟s Costs

50 – Capitalized Supplementary Costs (CSC)
51 – Shipping and Transportation Costs
52 – Spare Parts
53 – Taxes
54 – Insurance
55 – Initial Fuel Core Load
58 – Decommissioning Costs
59 – Contingency on Supplementary Costs

Accounts 10 + 20 +30 + 40 + 50 = **Overnight Construction Cost** (OCC)

60 – Capitalized Financial Costs (CFC)
61 – Escalation
62 – Fees
63 – Interest During Construction
69 – Contingency on Financial Costs

Accounts 10 + 20 + 30 + 40 + 50 + 60 = **Total Capital Investment Cost** (TCIC)

70 – Annualized O&M Cost (AOC)
71 – O&M Staff
72 – Management Staff
73 – Salary-Related Costs
74 – Operating Chemicals and Lubricants
75 – Spare Parts
76 – Utilities, Supplies, and Consumables
77 – Capital Plant Upgrades
78 – Taxes and Insurance
79 – Contingency on Annualized O&M Costs

80 – Annualized Fuel Cost (ASC)
81 – Refueling Operations
84 – Nuclear Fuel
86 – Fuel Reprocessing Charges
87 – Special Nuclear Materials
89 – Contingency on Annualized Fuel Costs

90 – Annualized Financial Costs (AFC)
91 – Escalation
92 – Fees
93 – Cost of Money
99 – Contingency on Annualized Financial Costs

Appendix B: Numerical GRA and AHP data

Table B.1: Grey relational coefficients for each attribute of each NPP

Attribute	EPR	LFR	LFR + DH
A11	0.333	1.000	1.000
A12	0.333	1.000	1.000
A13	0.333	1.000	1.000
A21	1.000	1.000	1.000
A22	0.333	1.000	1.000
A23	0.333	1.000	1.000
A31	1.000	0.333	0.333
A32	1.000	0.333	0.333
A33	1.000	0.333	0.333
A34	1.000	0.333	0.333
A41	1.000	1.000	0.333
A42	1.000	1.000	0.333
A51	1.000	1.000	1.000
A52	1.000	1.000	0.333
A61	0.333	0.333	1.000
TOTALS	**11.000**	**11.667**	**10.333**

Table B.2: the attributes divided in their hierarchy levels and their unjudged proportional relevance towards their parent index and main goal (bold).

Criteria			Sub criteria		
A1	Fuel cycle efficiency	0.1667 **0.1667**	A11	Fuel consumption	0.333 **0.0556**
			A12	Waste production	0.333 **0.0556**
			A13	Radio toxicity	0.333 **0.0556**
A2	Operational characteristics	0.1667 **0.1667**	A21	Load following flexibility	0.333 **0.0556**
			A22	Cooling water consumption	0.333 **0.0556**
			A23	Space requirements	0.333 **0.0556**
A3	Total costs ownership	0.1667 **0.1667**	A31	Capital costs	0.250 **0.0417**
			A32	O&M costs	0.250 **0.0417**
			A33	Fuel cycle costs	0.250 **0.0417**
			A34	D&D costs	0.250 **0.0417**
A4	Licensing procedure	0.1667 **0.1667**	A41	Licensing time	0.500 **0.0833**
			A42	Licensing uncertainty	0.500 **0.0833**
A5	Safety	0.1667 **0.1667**	A51	Active/ passive safety	0.500 **0.0833**
			A52	Public safety hazard	0.500 **0.0833**
A6	District heat generation	0.1667 **0.1667**			

Table B.3: Grey relational grades. These grades express each group ultimate preferred NPP

	EPR	LFR	LFR + DH
Nuclear scientists	**0,7538**	0,6592	0,5858
Utility exploiters	**0,8132**	0,6725	0,6530
NPP exploiters	**0,8539**	0,5904	0,5385
Citizens of Eindhoven	0,7115	**0,8109**	0,8070
Students	0,7121	**0,8519**	0,8087
Geometric mean	0,7257	**0,8153**	0,7418

Appendix C: Questionnaire

A pairwise comparison between nuclear power plant characteristics

Please save the completed file and return it to: t.p.b.v.d.wiel@student.tue.nl

Thank you for participating in this questionnaire! This questionnaire is a part of my graduation thesis in the major subject Construction Management and Engineering (CME) at the Eindhoven University of Technology. You are being asked to **anonymously** collaborate with this questionnaire and be part of the diverse group of nuclear scientists, utility exploiters, civil servants, nuclear power plant operators, inhabitants of Eindhoven and TU/e students that will hand in their opinion on what they think that matters to the future deployment of a nuclear power plant. Your or your company's name will not be published.

The context of this questionnaire will be explained below, followed by the questions which your judgement matters to. If you are well familiar to the pairwise comparison system and to the nuclear thesaurus, you can start the questionnaire right away at the next page. If not, please read the instruction and the thesaurus in the appendix. Good luck!

Context: An example of 3 discerning nuclear power plants

Below you see an example of three totally different types of nuclear power plants currently operated. All three are discerning and excel in a unique characteristic. What do you think is important, what characteristics do you prefer, and what should a future plant look like?

Olkiluoto Finland
(under construction)
1 x EPR 1600 MWe
Delivers 14.2 TWh/yr
of electricity to
> 1,000,000 people

Highly efficient in power output
Maximum value for money by economies of scale. The most proven and modern concept

Beznau Switzerland
2 x PWR 365 MWe
Besides electricity it delivers
150 GWh/yr of district heat
to 11 surrounding municipalities;
≈ 19,000 households

Highly efficient in total heat usage
Maximum thermal power efficiency by utilizing waste heat for district heating

Belojarsk Russia
1 x LMFBR 560 MWe
Delivers more fuel than it
consumes in the ratio of ≈ 1.2
Allows 75% energy usage of the
natural uranium instead of the
average 3% (in LWR's)

Highly efficient in fuel consumption
Maximum uranium utilization by breeding fissionable fuel and mitigating waste

Pairwise comparisons

PLEASE READ CAREFULLY

The pairwise comparison scores you are asked to give range from 1 to 9, where 1 is equally important and 9 is very strongly more important (see table below). Please give your opinion with a capital "X", you can fill in **only 1 "X" per comparison**.

Intensity of importance	*Definition*	*Explanation*
1	Equal importance	Two aspects contribute equally to the objective
3	Weak or slight	Experience and judgment slightly favour one aspect over another
5	More important	Experience and judgment favour one aspect over another
7	Strong importance	Experience and judgment strongly favour one aspect over another
9	Very strong importance	An aspect is favoured very strongly over another;

	9	7	5	3	1	3	5	7	9	
Fuel cycle efficiency										**Total costs ownership**
Fuel cycle efficiency										**Licensing process**
Operational /physical characteristics										**Fuel cycle efficiency**
Operational /physical characteristics										**Safety**
Operational /physical characteristics										**Licensing process**
Total costs ownership										**Operational /physical characteristics**
Total costs ownership										**Safety**
Total costs ownership										**District heating**

Licensing process	9	7	5	3	1	3	5	7	9	**Total costs ownership**
Licensing process	9	7	5	3	1	3	5	7	9	**Safety**
Licensing process	9	7	5	3	1	3	5	7	9	**District heating**
District heating	9	7	5	3	1	3	5	7	9	**Operational /physical characteristics**
District heating	9	7	5	3	1	3	5	7	9	**Safety**
District heating	9	7	5	3	1	3	5	7	9	**Fuel cycle efficiency**
Safety	9	7	5	3	1	3	5	7	9	**Fuel cycle efficiency**
Fuel consumption	9	7	5	3	1	3	5	7	9	**Waste production**
Waste production	9	7	5	3	1	3	5	7	9	**Radio toxicity**
Radio toxicity	9	7	5	3	1	3	5	7	9	**Fuel consumption**
Licensing time	9	7	5	3	1	3	5	7	9	**Licensing uncertainty**
Capital investment costs	9	7	5	3	1	3	5	7	9	**O&M costs**

	9	7	5	3	1	3	5	7	9	
Capital investment costs										**Fuel cycle costs**
Capital investment costs										**D&D costs**
D&D costs										**O&M costs**
D&D costs										**Fuel cycle costs**
O&M costs										**Fuel cycle costs**
Load following flexibility										**Space requirements**
Load following flexibility										**Cooling water consumption rate**
Cooling water consumption rate										**Space requirements**
Active/passive safety features										**Population within area**

THESAURUS

MWe	- Mega Watt electric	EPR	- European advanced Pressurized water Reactor
TWh/y	- Terra Watt-hours a year	PWR	- Pressurized Water Reactor
GWh/y	- Giga Watt-hours a year	LMFBR	- Liquid Metal–cooled Fast Breeder Reactor
		LWR	- Light Water Reactor

Fuel efficiency and waste mitigation:
The nuclear fuel cycle is split in two parts, namely the front end and back end. The front end consists of the processes of mining, milling, refinement, enrichment and fuel fabrication. The back end consists of interim storage (cooling down fuel assemblies), reprocessing, transmutation (mitigating radio toxicity) and waste disposal.

Fuel consumption:
The rate of heavy metal fuel assemblies that are used by the nuclear power plant.

Waste production:
The volume of radioactive assemblies that require *final* disposal, i.e. after reprocessing.

Radio toxicity:
Radiation level of the spent fuel that requires storage.

Operational and physical characteristics:
Some physical and operational characteristics of the plant need to be compared. These are limited to the actual requirements of land, the load following flexibility and the cooling water consumption.

Load following flexibility:
The power plant's ease to increase or decrease its power output when requested (depending on demand like in peak and off-peak hours).

Cooling water consumption:
The rate in which the plant uses surface water to remove excess heat from the power plant.

Space requirements:
The footprint of the power plant, expressed in square meters.

District Heat:
Excessive heat (over 60% of the reactor's thermal capacity) is mostly thrown away as waste heat. District heating is the utilization of this thermal power from the cooling water to warm houses within the area. District heating is one of features together with cogeneration and such to increase thermal efficiency of a plant and to optimize natural resources.

Levelized costs ownership:
The total costs of ownership, expressed as levelized costs, i.e. all costs during the lifetime of the plant are divided by its lifetime generated power output. This expression of costs allows the assessment of economic competitiveness between the alternatives.

Capital costs:
The upfront capital investments costs necessary to obtain and commission the new plant.

Operation and Maintenance costs (O&M):
All costs for operating the plant and for maintaining its components over its total lifetime.

Fuel cycle costs:
Costs for the purchase of nuclear fuel and the costs for spent fuel (waste) storage.

Decontamination and Decommissioning costs (D&D):
All costs for closing down the plant, decontamination of components, cleaning soil etc.

Licensing process:
Nuclear power plants are discernible by the long and effort intensive licensing procedures. Before starting such a procedure, it is important to create an awareness of the time and the risks that are coherent to the licensing procedure.

Licensing time:
Licensing time is the time needed to obtain a license for construction and exploitation of a nuclear power plant. Some procedures can take more than a year.

Licensing uncertainty:
Uncertainties in licensing procedures can be caused by a number of reasons, for example: uncommon or unknown risks to the health and environment, novel technology and safety aspects, exceptional surroundings and local resistance to a new nuclear power plant.

Safety:
Needless to say, nuclear power plants are built with lots of safety features, both active and passive. The safety features of a design will always be checked, inspected and approved before it can be built. Therefore, all Dutch nuclear power plants comply with the same regulations and safeguards regarding operational safety. However, the location is nonetheless of influence on the potential risks (like building in seismic active areas) and the potential harm to its environment (like building near a large city).

Active / passive safety features
Active safety features consist of the mechanisms that can actively reduce risks and stop harmful effects in case of incidents or accidents. An example of active safety is the emergency diesel generators that provide power in case the plant shuts down unintentionally. Passive safety features are means that will not require activation and will work automatically. An example of passive safety is when a boiling water reactor core loses cooling water, it also loses the moderator that is necessary to maintain a chain reaction, thus stopping further fission.

Population density within area
Another safety aspect is the average population size staying in the designated evacuation area at throughout the day. In case of a severe accident, these people need to be evacuated immediately.

Appendix D: Summary

AN EXPLORATORY STUDY ON THE COMPETITIVE POSITION OF A GENERATION IV NUCLEAR POWER PLANT IN THE NETHERLANDS

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Date of graduation
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Nations worldwide encounter energy provision related difficulties like air pollution, fossil fuel availability, reliability and security. The Dutch government set forth its aims in the reliable, affordable and clean policy stressing that the Netherlands should become less reliant on other countries, high prices and polluting fuels. New nuclear power plant permits have been turned down over the last three decades but the government is now open for issuing new permits. Thereby, the size of the market that can be supplied with electricity from Dutch power plants is increasing due to the expansion of the number of interconnections and increased integration with electricity markets in neighbouring countries. Consequently the share of nuclear power plants is expected to grow. At the time typical advanced light water reactors set the standard in technology and economics, however, prospective fast reactors hold an incredible potential in terms of resource utilization and waste management. This research explored the competitive performance of one type of fast reactor and compared it with a current established light water reactor through the use of Grey Relational Analysis (GRA) and Analytical Hierarchy Process (AHP) modelling. The results of the GRA show that the fast reactor has a higher overall performance technically however in sheer terms of economics the light water reactor excels. The stakeholders that were involved in the AHP rated the significance of costs related performance attributes clearly as predominant factor, which ultimately pleads for the light water reactor. Hence the light water reactor at this time is considered as most competitive.

Keywords: fast reactor, generation IV, competitiveness, Analytical Hierarchy Process, Grey Relational Analysis

Introduction
Natural gas is the most important and abundant natural resource in the Netherlands and the Dutch natural gas extraction accounts for one fifth of the European gas extraction. The Dutch have the highest natural gas consumption rate in Europe and besides, the Dutch are net exporter. The Netherlands cover more than 75% of their own energy needs compared to 60% on average in the rest of Europe, mostly due to natural gas.

However, it is concerning that - business opportunity or not - natural gas is not an exhaustless resource and will run out over the next decades. The Dutch ministry of Economic Affairs (EA) expects that by the midst of this century, the Dutch will become importer of natural gas instead of net exporter as today (EA, 2008).
Therewith, the negative environmental impact of energy production, transformation, handling and consumption becomes increasingly significant. Bearing these developments in mind, the future of the Dutch energy provision system will be under pressure. Therefore, it really needs thorough reconsiderations and at the time, there are only a few realistic options for securing national electricity generation; 'increase efficiency in electricity generation and use; expand use of renewable energy sources such as wind, solar, biomass, and geothermal; capture carbon dioxide emissions at fossil-fuelled (especially coal) electric generating plants and permanently disposal of the carbon and; increase use of nuclear power.'

When considering the nuclear option above, it is necessary that our understandings must be revised compared to the first nuclear era for continuing nuclear energy usage in the future. These understandings are mostly related to safety, management and storage of the high-level radioactive waste (HLW). Geological disposal is technically feasible but execution is not yet demonstrated or certain and not every European nation has pointed out, or is capable with long-term geological storage. Moreover, the Dutch government needs to decide on long-term waste deposit siting by 2016.
A fast reactor therefore appears a profound solution to mitigate the volume of spent fuel and HLW. Though at this point, there is no clear perception of the potential of revolutionary nuclear reactor systems – that are more sustainable in HLW management and mitigation– due to the lack of satisfactory demonstrated practical experience and urgency. Therefore, the trend has been to continue the utilization of typical light water reactors (LWRs). Additionally, the market entrance of newly developed nuclear power plants is generally a matter of financial profitability and capital risks.
The aim of this research is to tell if a more sustainable nuclear reactor can be part of our future energy mix. In other words, the aim is to disclose if a revolutionary nuclear reactor system; (1) can offer a sustainable solution to future energy challenges and; (2) is a competitive option on tomorrow's energy market.
This research effort focused on the generation IV nuclear reactor designs and the Lead-cooled Fast Reactor (LFR) was considered particularly.
The aim as explained above is dependent on the LFR's competitive economics and operational performance. Therefore, this research investigated the cost structure of this particular LFR system so it can be compared with the market supply systems. It then examined a tool by which mutual nuclear power plant performance can be measured.
The purpose of this tool is to assess the advantages and disadvantages of the LFR's performance compared to a current established LWR. For this assessment, prominent stakeholders' preferences are also taken into consideration, since they decide what is important.

Dutch energy provision

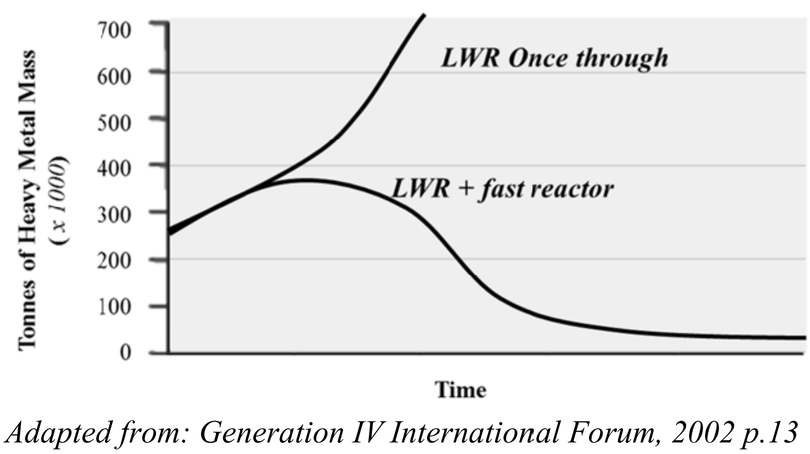
The annual energy demand of the Netherlands was approximately 128 TWh in 2007 (ECN, 2007). Industry is the most energy consuming sector, mostly due to the large (petro) chemical industry and greenhouse farming. More than half of the industrial energy consumption concerns the use of energy commodities as raw materials for processing products like plastics from petroleum. Petroleum is only extracted in small amounts on Dutch soil and therefore it has the biggest share of imported energy commodities, followed by coal which was extracted in the Netherlands before it became uneconomical.

Natural gas is the primary fuel used for electricity generation in the Netherlands and contributes to the total national electricity production for over more than 60%. A small amount of electricity is generated by the single currently operated nuclear power plant Borssele (approx. 485 MW) in the southwest of the Netherlands, which accounts for about 1.3% of the Dutch energy consumption. Speaking in sheer electricity terms this share is higher and the currently operated Borssele reactor provides about 4% of total generation, namely 4.1 TWh net in 2007 (WNA, 2011). In 2007, a total of 103 TWh gross was generated. Natural gas provided 60 TWh, and coal 28 TWh. Renewables (mostly biomass) added 8.7 TWh (WNA, 2011).
Regarding the demand structure, the future tells that it will increase ever due to an increasing population, technology advancements and a strong GDP (Statistics Netherlands, 2007). The European that can now be provided with electricity from the Netherlands will stress this demand even further.

Generation IV nuclear advancements

As explained in the introduction, nuclear power systems need to be advanced to meet future needs. To support these advancements, several nations cooperating as the Generation IV International Forum (GIF) have formed a framework for international cooperation in research. They stated their intentions and research objectives in a technology roadmap that serves a future generation - Generation IV - nuclear energy systems. The Generation indication stands for the contemporary nature of the nuclear reactor design and stage of technology. Some Generation IV nuclear reactors – like the LFR – are distinguished by a closed fuel cycle with recycling.
For this research, a closed fuel cycle with fully recycling is of topical interest. Namely, closed fuel cycles could include the use of a dedicated fast reactor that can be used to breed fissile material or can be used for the transmutation of selected isotopes that have been separated from spent fuel, burning as it were, the highly radioactive material. When the LFR is designed to transmute actinides from spent LWR fuel, nearly all long-lived actinides can be transmuted to short-lived isotopes, which would: (1) reduce the amount of radioactive waste that needs deep repository to a fraction of what is needed for once-through cycle, and; (2) by removing the actinides (Americium, Neptunium, Curium) the radioactivity would be significantly reduced within 100 years (Hore-Lacey, 2006).
The sustainable property of the closed fuel cycle with fully recycling has a very evident effect on permanent waste storage as shown in figure 1.

Figure 1: Spent fuel inventory with and without the introduction of fast reactors



Adapted from: Generation IV International Forum, 2002 p.13

For this research effort, the Lead-cooled Fast Reactor (LFR) was considered. 'The LFR system is top-ranked in sustainability because a closed fuel cycle is used, and in proliferation resistance and physical protection because it employs a long-life core. It is rated good in safety and economics.' (GIF, 2002) The safety is enhanced by the choice of a relatively inert coolant (Pb) compared to sodium for example.

For this research effort on the LFR system, data of the European Lead-cooled fast reactor SYstem (ELSY) design is adopted as a reference design. All further used data, characteristics and calculations are based on this specific ELSY design. 'The ELSY reference design is a 600 MWe pool-type reactor cooled by pure lead. Sustainability was a leading criterion for option selection for core design, focusing on the demonstration of the potential to be self-sustaining in plutonium and to burn its own generated MAs.' (Alemberti et al, 2009)

Integrated Nuclear Energy Economics Model

To determine the economics of Gen IV systems, the GIF has set up the Economic Modelling Working Group (EMWG). The EMWG is in charge of the development of future generation cost estimation methods. They proposed the Integrated Nuclear Energy Economics Model (INEEM). The EMWG Code of Accounts (COA) system and G4ECONS excel based computing software were used to calculate the costs of the concerning LFR as no data of the costs is yet available. The accounts that were used can be found in the GIF-EMWG cost estimating guidelines (GIF-EMWG, 2007).

The ultimate aim of the costs calculations is to determine the LFR's levelized unit of electricity costs (LUEC). The LUEC expresses the euros it costs to generate one MW of electricity. The purpose of the LUEC is that this figure makes it is now comparable to other electricity generating systems. This is important to determine its economic competitiveness.

Two plant cost models were considered, namely a first-of-a-kind (FOAK) plant, because there are no specific LFRs of this type to date and an nth-of-a-kind (NOAK) for identical follow up LFRs. Because of the goal is to find out if the LFR could be a competitive attractive option; the NOAK plant cost figures will further be used to assess its economic advantages, assuming that market parties will only opt for a LFR after it is fully demonstrated.

The calculations have been carried out un G4ECONS and processed in table 1. For the plant, two different discount rates were taken into consideration namely: the 5% discount rate and the 10% discount rate, so that it can be compared with the other source of energy generation in the future.

Table 1: Results of the INEEM for the *NOAK* LFR power plant expressed in 2009 €/MWh

	discount rate 5%	discount rate 10%
Capital costs including financing	34.80	87.75
Operation	7.29	10.58
Fuel cycle front end	6.86	12.51
Fuel cycle back end	2.24	4.78
Fuel cycle total	9.10	17.29
D&D sinking fund	0.017	0.04
Specification TCIC	5,549	6,360
Total LUEC	**51.36**	**115.66**

When evaluating the future market developments with e.g. the International Energy Agency's 'Projected Costs of Generating Electricity – 2010' (IEA, 2010), some remarkable developments take place. Simply put, fossil fuels costs will go up and renewables costs will go down; the LUECs of these electricity sources are highly influenced by future policy objectives and market developments. It almost comes to a turning point where these sources trade places; except for the fact that renewables still are doubtful regarding their practical feasibility.
Regarding nuclear energy (generation II/III), little changes will occur. Nuclear fuel will remain extensively available and the European share in nuclear hardly increases (IEA, 2009). Nuclear energy will remain highly competitive in terms of economics for at least this century and because it does, the LFR will not become anywhere near competitive with these older systems. Nevertheless the LFR can be financially competitive with fossil fuel fired power plants and renewables.

Multi attribute decision making tool
The competitiveness beyond mere economics is finally measured in comparison with another nuclear power plant (NPP). Namely this comparison it is done with an European Pressurized water Reactor (EPR) that is most plausible to be built in the Netherlands in the near future. The final part of this research is the mutual classification of both the LFR's and the EPR's configurations with the help of a multi-attribute decision making (MADM) tool. From these configurations, 15 performance attributes were extracted for comparison as shown in table 2 which are expressed in figures. Henceforth, two methods are introduced to rank these performance attributes by both mathematical relativisation and by stakeholders' judgements. To elaborate such MADM tool, two methods are introduced, namely the Grey Relational Analysis (GRA) and the Analytical Hierarchy Process (AHP).

Table 2: nuclear power plant configurations and their performance attributes

Attribute:			EPR	LFR
A11	Fuel consumption	*mt/yr* [1]	1.35E-04	9.18E-05
A12	Waste production	*mt/yr*	2,46	1,15
A13	Radio toxicity	*Svt/TWh* [2]	1.85E+10	2.29E+07
A21	Load following flexibility	*%*	100	100
A22	Cooling water consumption	10^5 m^3/hr [3]	4.914	1.552
A23	Space requirements	*hectare*	8,571	8,498
A31	Capital costs	*€/kWh* [4]	52.78	80.93
A32	O&M costs	*€/kWh*	8.34	10.62
A33	Fuel cycle costs	*€/kWh*	5.33	9.10
A34	D&D costs	*€/kWh*	0.030	0.048
A41	Licensing time	*months*	36	36
A42	Licensing uncertainty	*%* [5]	25	25
A51	Active/ passive safety	*%* [6]	100	100
A52	Public safety hazard	p/km^2 [7]	160	160
A6	District heat generation	*GWh/yr*	0	0

[1]: metric tonnes per year
[2]: decay radiation in Sievert per Terawatt-hour
[3]: 100,000 litres per hour
[4]: costs A31-A34 are derived from the standard 10% discount rates
[5]: 25% means low uncertainty, proven concept. 75% means high uncertainty, unusual concept
[6]: due to very strict safety regulations concerning plant licencing, plants perform equal
[7]: accommodated population per square kilometre within the vicinity on average

Grey relational analysis
According to literature (e.g. Lee and Lin, 2011; Kung and Wen, 2007; Wei, 2011):
'GRA is proven to be useful for dealing with problems under discrete, poor, fragmented, incomplete and uncertain data sets and solving their complicated inter-relationships between the multiple factors and variables. In GRA, the global comparison between multiple sets of data is undertaken instead of using local comparison by measuring the distance between two points. It measures the degree of similarity or difference between two sequences or discrete data sets based on the grade of relation.'
With the LFR still in the design phase, its operational performance figures are based on calculations until demonstration experience is measured in practice. For the EPR goes that its performance data is either factory released, i.e. data is provided by the supplier, or calculated.

GRA procedure
The main procedure of GRA consists of four steps: Grey relational generating, reference sequence definition, Grey relational coefficient calculation, and Grey relational grade calculation (Lee and Lin, 2011). In Grey relational generating step, GRA firstly translate the performance of all alternatives into comparability sequences. According to these sequences, a reference sequence (ideal target sequence) is defined at reference sequence definition step. Then, the Grey relational coefficient between all comparability sequences and the reference sequence is calculated. Finally, based on these Grey relational coefficients, the Grey relational grade between the reference sequence and every comparability sequences is calculated. If a comparability sequence translated from an alternative has the highest Grey relational grade, that alternative will be the best choice.

The sum of the Grey relational coefficients for each plant after calculations is shown in table 3, where goes, the higher the sum, the closer the NPP is to the optimum sequence.

Table 3: Grey relational coefficients

	EPR	LFR
Summed Grey relational coefficients	11.000	11.667

Clearly the LFR rates higher than the EPR. Thus it can be said that the LFR does hold the best overall performance. These Grey relational coefficients however do not hold any factor of importance. Although, the LFR rates highest, another nuclear power plant might still be best when considering the significance of these weights.
These weights usually depend on the decision maker's judgements (Lee and Lin, 2011). Though, this can be done in a setting where the modeller is the stakeholders or where stakeholders are closely involved in the decision making process, it is less suited for these circumstances.

AHP procedure
The AHP procedure consists of the following steps: first, the hierarchal structure needs to be designed which arranges all the criteria and sub-criteria. The criteria are used to label rows and columns of the pairwise matrix, called the comparison matrix. At each level of the hierarchal structure, a pairwise matrix is created according to the corresponding (sub-) criteria. The next step is to fill the intersections between them with a numerical preference value. These preferences values can be obtained by stakeholder judgments by means of a questionnaire. Then, the judgements are checked for consistency. Thereafter, the matrices'

eigenvector is calculated by normalising the values of each row. The resulting eigenvector is the principal eigenvector elucidating the relative preferences for each of the alternatives.
The preference values extracted from these questions were collected through individual questionnaires. Five different groups of respondents were selected as prominent stakeholders, namely: nuclear physicists and researchers; utility exploiters not operating a NPP in their energy portfolio; nuclear power plant exploiters; citizens of Eindhoven and; students from the University of Technology Eindhoven of the major subject Construction Management and Engineering.

They were asked to individually compare each criterion with the next, repeatedly until all criteria were compared to one and another. The respondents had to use the scale from 1,3,5,7,9 where 1 is equal important and 9 is very strongly more important.

Furthermore it was chosen to perform a rather qualitative than quantitative questionnaire. The number of respondents of each group invited to the questionnaire had a minimum of two and a maximum of five. This was done because of two reasons; (1) there is only one commercial nuclear power plant in the Netherlands, what makes it impossible to ask a large population of nuclear power plant exploiters, and; (2) the pairwise comparison method demands carful considerations, and expectations were that mostly citizens and students are not able to return perfect consistent questionnaires, making large populations even more unusable.
The results from the questionnaires were processed into table 5. Of the other groups, five nuclear scientists replied, two utility exploiters, two nuclear power plant exploiters, five citizens of Eindhoven and five students of the University of Technology Eindhoven.
The ratings in table 5 show the individual group's ratings of the importance of each criteria. The highest rating of each group is expressed in bold.

With the calculated Grey relational coefficients and with the results of the questionnaire, each groups' most preferred NPP can be distinguished. This 'ideal' NPP is expressed by the highest Grey relational grade. The final grades that were generated are represented in table 6 below.

Table 5. Stakeholder's ratings of each performance attribute

	Nuclear scientist	Utility exploiters	NPP exploiters	Citizens of Eindhoven	Students
Fuel consumption	0,0258	0,0633	0,0376	0,0837	0,0382
Waste production	0,0439	0,0331	0,0345	0,0986	0,0921
Radiotoxicity of waste	0,0290	0,0134	0,0106	0,0565	0,1524
Load following flexibility	0,0790	0,0787	0,0178	0,0351	0,0683
Cooling water consumption	0,0236	0,0098	0,0071	0,0235	0,0225
Space requirements	0,0112	0,0141	0,0148	0,0235	0,0235
Capital costs	0,1603	0,1521	0,3103	0,0173	0,0445
O&M costs	0,0545	0,1165	0,0836	0,0477	0,0353
Fuel cycle costs	0,0293	0,0380	0,0678	0,0491	0,0139
D&D costs	0,0313	0,0383	0,0382	0,0225	0,0254
Licensing time	0,0191	0,0442	0,0396	0,0417	0,0169
Licensing uncertainty	0,0804	0,0066	0,0396	0,0474	0,0253
Active/ passive safety features	0,1958	0,2472	0,1876	0,2734	0,2706
Population within area	0,1800	0,0934	0,0839	0,0560	0,1113
District heating	0,0366	0,0515	0,0270	0,1239	0,0598

Table 6: Grey relational grades. These grades express each group ultimate preferred NPP

	EPR	LFR
Nuclear scientists	**0,7538**	0,6592
Utility exploiters	**0,8132**	0,6725
NPP exploiters	**0,8539**	0,5904
Citizens of Eindhoven	0,7115	**0,8109**
Students	0,7121	**0,8519**
Geometric mean	0,7257	**0,8153**

It is the industry that ultimately judges which NPP is economically attractive and therefore which power plant will be deployed in the future. Thus, with costs rated as the major driving forces, the LFRs performance will not be competitive enough to become feasible on the short term.

Conclusion

At the moment, the Dutch energy provision is incredibly dependent on its natural gas resources that – on the short term – cause volatile market developments because of the high export standards and pricing and – on the long term – will become an evident difficulty when depletion comes closer.

The LFR certainly has benefits for the futures energy mix when considering its stability, waste burning capability and fuel utilization. In addition, nuclear power plants are one of the few remaining type of power plants that can continue to deliver electricity in environmental friendly and reliable ways. The present Dutch government stated that the security of energy supply would remain a policy spearhead, along with efforts to cut carbon dioxide emissions in line with European targets. Hence "the government will be open to issuing permits for new nuclear power plants." Another spearhead of the present government's policy is that 'energy security must be increased and more attention must be paid to the potential profitability of energy'. In terms of security, the LFR will perform excellent, however, in terms of profitability, the current and future Gen III/III+ LWR reactors will prevail. In addition, the capital at risk is far higher than with the current generation nuclear power plants.

The investigated LFR is not competitive compared to an EPR, nor is the closed fuel cycle with full recycling compared to the once through cycle at this moment. The share of nuclear power plants will not increase drastically next decades. The urge to make the transition to closed fuel cycles with fully plutonium recycling and burning minor actinides will probably not be made in the 21st century as costs of uranium will not likely rise that fast.

The MADM tool has proven to be useful in the assessment of the advantages and disadvantages of the two compared nuclear power plants. The results clearly show that the LFR has the highest Grey relational grade which indicates a slightly higher overall performance. This is mainly due its fuel and waste handling characteristics. When the stakeholders' opinions are taken into consideration, the best performance becomes twofold. Namely the industry rates the EPR as best performing, whilst the non-industry rates the LFR as best performing. This conclusion shows that the non-industry – confirming to the general survey that was held nationwide (Smart Agent Company, 2009) – perceives the waste-handling performance of a LFR as the key performance indicator. On the contrary, the industry pointed out capital investment costs as the major key performance indicator.

Discussion

Only the potential of fast reactors in general was investigated and the research proceeded with taking only one very particular Gen IV reactor into consideration. The competitiveness of other Gen IV reactors remains therefore unknown and will be of interest in further research.
The costs input for the LFR came from preliminary designs as the input form the EPR mostly came from the supplier and can therefore differ from reality. This unfairness was straightened out by running the EPR data through the same G4econs model as the LFR was calculated with. The fact still remains that the EPR is already under construction today and comparison will be more reliable when the LFR becomes in the same advanced stadium. It goes for the investigated LFR that it is not operational before 2040. Therefore, when the LFR becomes in a further design phase where more detailed costs estimations can be made, it can be recommended to review its cost competitiveness.
Furthermore, the LFR has been compared with an EPR. This EPR however, is developed with different objectives in mind. Comparison between these two might not reveal as much information as when the tool would be used to compare nuclear power plants of the same technical scope and objectives. Consequently a logically step would be to use the MADM tool to compare future Gen IV systems or even more particular Gen IV lead-cooled systems when more of these systems' technical data becomes available.

Recommendations

Nuclear is a mature technology and no specific incentives are needed. It could easily be the backbone of the Dutch national energy provision, once gas production is near exhaustion. The Dutch government then needs to seek ways for skimming proportional profits so that all the Dutch share benefits. However, for nuclear energy to be really cost effective and to really be a source of energy future generations can rely on, the Dutch government needs to formulate clear policies and probably have to cooperate with both utility companies as civilians in order to match interests. High upfront costs of investment in these facilities again make the issue of regulatory uncertainty crucial; as long as this is not clear, no investor will risk their money on a LFR waste burner or on reprocessing infrastructure. As for now; every EU member state has to deal with the nuclear waste issues themselves. It would be sensible that the Dutch government considers these investments and infrastructure for high radio-active waste in cooperation with neighbouring countries.

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Appendix E: Over the author

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In my study career, I educated myself mostly by schools for vocational education. During secondary school, I gradually got more interested in technology in practise, so I decided to follow vocational training from fourth grade on. This is a somewhat unique training process in the Netherlands, because it is more common to go to a university after graduating on secondary school. I finally decided to apply to the university to obtain a master in science degree, to be able to adapt theoretical knowledge and way of thinking and synchronize it with my practical background. Completing the challenging and long way to a university pays of in technical and everyday practise and I still enjoy this decision on daily basis.

Education

2008 – present	Eindhoven University of Technology; Research University	Master subject: Construction Management & Engineering
2005 – 2008	HAN; University for Professional Education	Bachelor subject: Architecture and Planning
2001 – 2005	Rivierenland College; Senior Secondary Vocational Education	Subject: Construction/Architecture