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for Cogeneration of
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Key Performance Indicator Definition

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Summary

Within the current Key Performance Indicator assessment, a number of key performance indicators are defined as a basis for comparison between HTR cogeneration and a reference gas-fired cogeneration plant. The purpose is to identify pathways towards improved emloyment of HTRs, specifically with respect to the performance when being used for cogeneration. An attempt has been made to provide an objective overview of the different indicators important for decision makers. One should realize that the decision to construct an HTR or another energy generation facility are not only technical, not only economical, but are highly influenced by public opinion and politics. Therefore, it is impossible to draw firm conclusions. However, some generic conclusions may be drawn: - An HTR system can be considered economically viable in Europe when it is employed for the production of electricity and process heat. - A demonstration of an HTR with cogeneration will be a very important step, as it will remove the current uncertainties associated with licensing and time to market. - The environmental impact of an HTR is minimal, as long as the safety features claimed are true. - There seems to be a lower boundary of the break-even ratio of process heat and electricity price. This means that the price for process heat should be at least a certain percentage of the price of electricity for a coupled system to become profitable. This value may vary from case to case.

Approval

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Definition and Application of Comparative Key Performance Indicators

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- An HTR system can be considered economically viable in Europe when it is employed for the production of electricity and process heat.
- A demonstration of an HTR with cogeneration will be a very important step, as it will remove the current uncertainties associated with licensing and time to market.
- The environmental impact of an HTR is minimal, as long as the safety features claimed are true.
- There seems to be a lower boundary of the break-even ratio of process heat and electricity price. This means that the price for process heat should be at least a certain percentage of the price of electricity for a coupled system to become profitable. This value may vary from case to case.

1 Introduction

High Temperature Reactors (HTRs) are being considered for deployment around the world. An HTR uses helium gas as a coolant, while the moderator function is accomplished by graphite. The fuel is embedded in the graphite moderator and can sustain extremely high temperatures, basically preventing the fuel from melting. An important feature associated with the HTRs, is the high coolant temperature that can be achieved and therefore high electric efficiency. The high coolant outlet temperature also leads to optimal suitability for coupling the reactor to an industrial process requiring heat.

In order to identify pathways towards improved emloyment of HTRs, specifically with respect to the performance when being used for cogeneration, a number of key performance indicators are defined as a basis for comparison between HTR cogeneration and a reference gas-fired cogeneration plant for the same purpose.

The identified KPIs are subdivided into:

- Plant characteristics,
- Environmental KPIs,
- Safety KPIs,
- Economic KPIs.

Plant characteristics basically are needed to work out the other KPIs. This KPI assessment further elaborates and tries to quantify the KPIs with respect to the environment, safety, and especially those on economic KPIs. For the latter, a top-down cost estimate for a typical reference HTR has been produced. In the assessment, it was assumed that the HTR demonstration phase has been successfully completed which means that an n^{th}-of-a-kind reactors can be considered. Referring to figure 1, this means that the first commercial projects are being operated which should be feasible in about 20 years time. This top-down cost estimate provides input for a system economic analysis using the G4Econs tool which is produced by the Economic Modeling Worker Group (EMWG) of the Generation 4 International Forum (GIF).

Within chapter 2, the considered KPIs are introduced and in chapter 3 the reference plants considered in this KPI assessment are described. Chapters 4, 5, 6, and 8 present the KPIs given in chapter. Chapter 7 elaborates further on the economic evaluation which forms the basis of the economic KPI assessment presented in chapter 8. Finally, conclusions are presented in chapter 9.

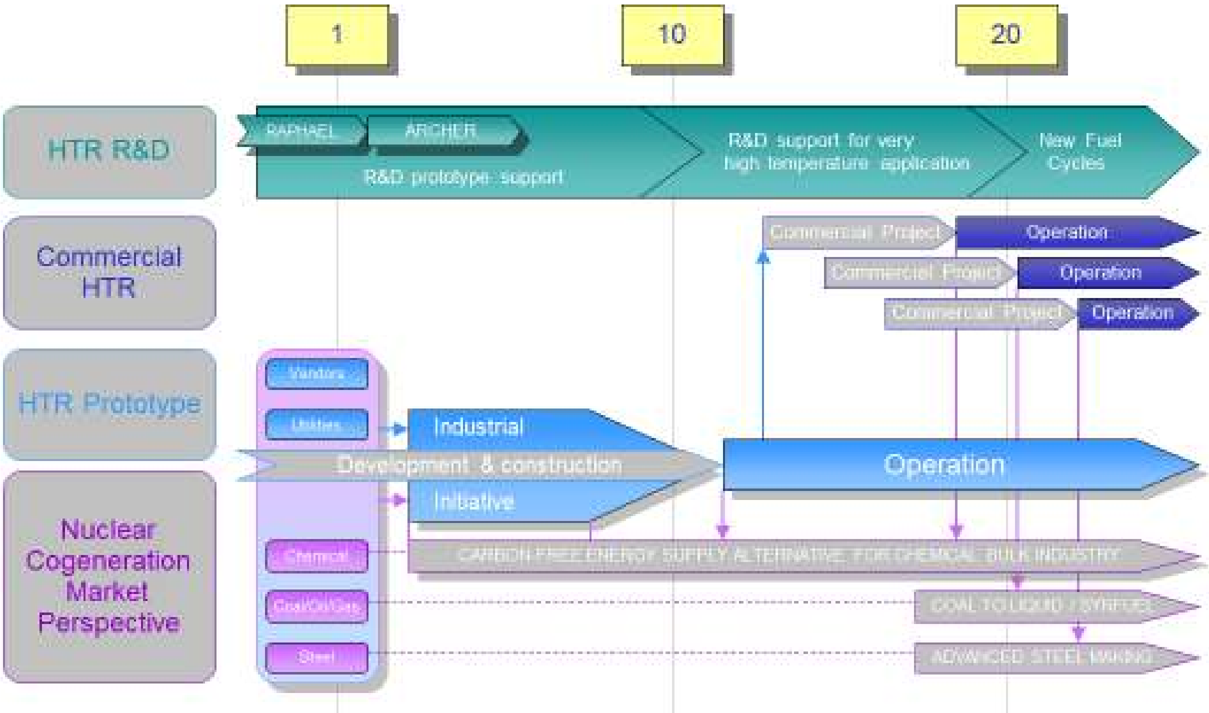

Figure 1: Updated HTR Roadmap initiated in the EU FP7 EUROPAIRS project (De Groot et al., 2013)

2 Definition of Key Performance Indicators

A preliminary list of Key Performance Indicators (KPIs) was derived and discussed with ARCHER SP1 participants in the 2012 meeting in Jülich and the 2013 meeting in Dresden. Some minor changes were made during the performance of the work. The final definition of KPIs is given below in table 1. The KPIs have been divided in four categories, i.e. plant characteristics KPIs, environmental KPIs, safety KPIs, and Economic KPIs. The evaluations of these KPIs will be presented in the following chapters for the reference Combined Cycle Gas Turbine plant and a reference HTR which will be discussed in the the next chapter.

Table 1: Definition of Key Performance Indicators

Plant Characteristics	Environmental	Safety	Economics
Power Level	CO_2 Emission	Worker Injuries	Construction Costs
Availability	Sanitary Landfill Waste	Evacuees	O&M Costs
Design Lifetime	Chemical Waste	Fatalities & Injuries	Fuel (Cycle) Costs
Time to Market	Radioactive Waste	Licensability	Decommissioning
Construction Duration	External Costs		Generation Costs
Space Requirements			

3 Reference Plants

3.1 Combined Cycle Gas Turbine

Carlsson et al. (2012) explain that natural gas industrial boilers or natural gas firing are currently the easiest route to produce heat in the form of steam. Boilers typically have high thermal efficiencies of about 90%. A boiler can be ramped up quickly and the low investment cost allows it to be switched on and off with only limited economic penalty. Operation and maintenance are also little demanding.

Combined heat and power plants today using natural gas or coal as fuel, are economically more efficient. These produce electricity as high value commodity whilst meeting the heat demands of industrial sites of any size.

As in Carlsson et al (2012), a CCGT natural gas plant that produces electricity with high efficiency and heat will serve as reference for conventional fossil fired power plant in the current KPI study. Because of their economic analysis, the CCGT plant described by Locatelli & Mancini (2010) is taken as reference for many KPIs in this study.

3.2 HTR

There are several HTR designs available in the open literature. However, within the ARCHER project, Freis (2013) has described a nuclear heat source for a combined heat and power plant which is taken as reference for the current KPI study. Although it is recognized that this design may be based on an existing HTR design to which some objections towards the safety approach exist, for the current study this is considered to be of negligible influence.

For the HTR system considered, an n^{th}-of-a-kind is assumed. The HTR technology and economic demonstration phase has been excluded from this study. It has been assumed to be successfully ended, without much change to the current economic, safety and technical insights with regards to HTR technology.

4 Plant Characteristics KPIs

KPI	Unit	Gas Fired Plant	HTR
Power Level - **Thermal** - **Electric** - **Process Heat**	 - **MWth** - **MWe** - **t/hr**	 - 590 - 335 -	 - 2x260 - 127 - 400
Availability	**%**	90	90
Design Lifetime	**yr**	40	40
Time to Market	**yr**	0	10
Construction Duration	**yr**	3	5
Space Requirements	**m^2**	~50000	~50000

4.1 Power Level

The total power level of the reference CCGT should be of the same order of magnitude as the power level of the HTR nuclear heat source described by Freis (2013). The CCGT described by Locatelli & Mancini (2010) fulfils this requirement, having a power level of 590 MWth compared to 520 MWth for the HTR. As in the analysis of Locatelli & Mancini (2010) the CCGT was not used as cogeneration plant, but merely as a electricity production plant, no details about the process heat were supplied. The economic analysis in the current report takes this into account. Freis (2013) has assumed a design point of 127 MWe and 400 t/hr process heat, which is based on the data provided in the case study of Prochem (2012).

4.2 Availability

The availability of both the CCGT and the HTR is similar and provided by Locatelli & Mancini (2010) and Freis (2013) respectively.

4.3 Design Lifetime

The design lifetime of both the CCGT and the HTR are similar and provided by Locatelli & Mancini (2010) and Freis (2013) respectively. Many new nuclear stations within Europe albeit water cooled (and for electricity generation) are being developed for a +60 year lifetime which if adopted for HTR may offer some further advantage over the CCGT considered in the comparison.

4.4 Time to Market

The development time is defined as the time needed before a plant can be ordered. It is assumed that a CCGT can be ordered 'off-the-shelve'. Therefore, the development time is assumed to be 0.

With respect to a pebble bed HTR, the technology has been demonstrated previously in Germany and has been taken further towards commercialisation by PBMR in South Africa. Currently, the first modular pebble bed reactor (HTR-PM) is under construction at Weihai city (Shidaowan) in China. Noteworthy is that this demonstration plant is already of commercial size. However, even for an HTR-PM with cogeneration application, more time will be needed. Taking into account the fact that the European design will be different from HTR-PM and will need some years to develop in a sufficiently mature detailed design, and taking into account that the interface with the industrial process heat user is available only in conceptual design, a development time of about 10 years is selected. This assumes a successful demonstration phase has been finalised, in which the technology readiness, safety, and economics have been confirmed.

4.5 Construction Duration

The construction duration of a CCGT plant is provided by Locatelli & Mancini (2010). They provide a value of about 3 years. A similar value is mentioned in the publication of Bredimas (2012). For an HTR, there is a lot of debate about the construction duration. An HTR is not an off-the-shelf product yet for which production times can be based on experience. Bredimas (2012) provides a value of 4-6 years. Therefore, 5 years has been selected for the current study. It should be noted that this is still much shorter than a water cooled nuclear system which may take upwards of 10 years.

4.6 Space Requirements

Space requirements for the HTR plant can be derived from Freis (2013) and are in the order of 41000 m^2. For a CCGT, space requirements are seldomly published. Wrexham Power Limited (2013) provide a site plan for a 1000 MW CCGT plant existing of 2 units which would require approximately 10-15 hectares. This would mean approximately 50000 m^2 for a single plant of the size envisaged in the current study. Therefore, it is concluded that both plants, HTR and CCGT, will be of similar size which will be approximately 50000 m^2.

5 Environmental KPIs

KPI	Unit	Gas Fired Plant	HTR
GHG Emissions	**$kgCO_2eq/MWh$**	400	6
Conventional Waste	**kg/GWh**	34000	8000
Chemical Waste	**kg/GWh**	1500	1000
Radioactive Waste	**m^3/TWh**	0.02	9.7
External Costs	**ct/kWh**	0.29	0.06

5.1 Green House Gas Emissions

The emissions of Green House Gas (GHG) are provided both as actual amount, but also sometimes in comparison to a reference GHG emitting coal fired power plant. The actual amounts are provided by several resources. Spadaro et al. (2000) provide values in the range of 106-188 $kgCO_2eq/MWh$ for CCGT and 2.5-6 $kgCO_2eq/MWh$ for nuclear. The EC (2008) provides lifecycle emission values of 145-420 $kgCO_2eq/MWh$ for CCGT with and without carbon capture and storage and about 15 $kgCO_2eq/MWh$ for nuclear. Dones et al. (1998) provide lifecycle emission values of 390-600 $kgCO_2eq/MWh$ for current and future CCGT and 6 to 16 $kgCO_2eq/MWh$ for current and future nuclear technology. Considering nuclear (typically light water reactors), the amount of GHG emissions is depending on emissions during erection of the plant and the fuel cycle facilities but mainly on the fuel burn-up, the reactor efficiency, the mining, and the enrichment method. It should be mentioned that, compared to current light water reactors, an HTR with cogeneration will employ a much higher efficiency, and therefore, will have a lower specific emission value. Therefore, the low range of the values provided in literature is selected.

For the current KPI assessment, values of 400 $kgCO_2eq/MWh$ for CCGT and 6 $kgCO_2eq/MWh$ for nuclear are selected.

5.2 Conventional Waste

Hirschberg & Dones (2000) provide values for the sanitary landfill waste of different energy generation technologies. Sanitary landfills are sites where waste is isolated from the environment until it is safe. It is considered safe when it has completely degraded biologically, chemically and physically. In other words, it is a dump for conventional waste. This waste type is related to inert materials, especially from the construction sector and mining. From their assessment, it is clear that CCGT leads to about a fourfold the amount of waste as nuclear technology. The respective values are 34000 kg/GWh and 8000 kg/GWh for CCGT and nuclear respectively.

5.3 Chemical Waste

Hirschberg & Dones (2000) provide values for the chemical landfill waste of different energy generation technologies. This waste type is related to inorganic waste with potentially high concentration of pollutants. From their assessment, it is clear that CCGT leads to about 1.5 times the amount of chemical waste as nuclear technology. The respective values are 1500 kg/GWh and 1000 kg/GWh for CCGT and nuclear respectively.

5.4 Radioactive Waste

Hirschberg & Dones (2000) provide values for the radioactive waste of different energy generation technologies. They make a distinction between low and short-lived medium level radioactive waste, and high and long-lived medium level radioactive waste. For the current assessment, only the high and long-lived medium level radioactive waste are considered. They mention that ‘not surprisingly the nuclear systems generate by far the largest amounts of radioactive wastes. Within the life cycle analysis approach an appropriate share of radioactive wastes is also allocated to non-nuclear systems, mostly resulting from the electricity mixes used to support various stages of the energy chains.’ Obviously, especially for coal and gas, the mining or retrieval industry produces also nuclear waste. For CCGT they provide a value of 0.02 m^3/TWh. For nuclear (light water reactors) they provide a value of about 5 m^3/TWh.

However, following the data provided by Freis (2013) for a reference HTR, the following estimate can be made for an HTR. Assume that the high level radioactive waste originates for the largest part from spent fuel. Freis (2013) mention that 180 pebbles per day per reactor are required to refuel an equilibrium core. This means 360 pebbles per day per plant consisting of 2 reactors. Given an availability of 90%, this means that 118260 pebbles are disposed of per year. Assuming that the graphite pebbles containing the spent fuel are disposed without further spent fuel handling, the total waste volume can be calculated. Taking into account the volume of a spherical pebble with a diameter of 6 cm, the total volume to be disposed is 13.4 m^3/yr. In order to compare with the values provided by Hirschberg & Dones (2000) who have normalized the values with the energy produced, the total amount of electricity which can be produced with the reference HTR is considered. Although the design point for the reference HTR is 127 MWe and 400 t/hr process heat, for the current assessment it is assumed that the HTR is used to produce electricity only. This should compensate to some extent for the energy which is produced but is not converted into electricity but into process heat. Following Zhang et al. (2009), an electric efficiency of 42% is assumed together with a thermal energy production of 520 MWth (Freis, 2013). With an availability of 90% this means 1.72 TWh/yr. This means that the total radioactive waste for the HTR can be calculated at 7.8 m^3/TWh. Note that this figure does not take into account the possibility of reducing this volume further by removing the graphite from the waste form, which will have a very large impact and needs to be developed and brought to industrial scale which is not a trivial task.

5.5 External Costs

External costs of CCGT and nuclear are taken from the EU FP6 New Energy Externalities Developments for Sustainability (NEEDS) project. This project presents quantifiable external costs related to the operation of emerging electricity generation technologies in their NEEDS (2009) report. External costs can be defined as those costs which are not paid by those who generate it. Typically, these costs include the costs implications from e.g. pollution and land use. The quantification of external costs is based on the 'impact pathway' methodology. The impact pathway analysis aims at modelling the causal chain of interactions from the emission of a pollutant through transport and chemical conversion in the atmosphere to the impacts on various receptors, such as human beings, crops, building materials or ecosystems. Within the NEEDS study, the economic effect of airborne pollutants (fine particles), biodiversity losses because of land use, damage costs of greenhouse gases, Welfare losses resulting from these impacts are transferred into monetary values based on the concepts of welfare economics. The external costs are calculated by multiplying the relevant life cycle inventory data with the unit damage costs as explained in NEEDS (2009). For the current KPI assessment, the values for a near future CCGT plant are compared to the values for a near future nuclear power plant. These values are 0.29 ct/kWh for CCGT and 0.06 ct/kWh for nuclear.

6 Safety KPIs

KPI	Unit	Gas Fired Plant	HTR
Worker Injuries	**#/TWh**	6	6
Evacuees	**#/Gwe yr**	10	0
Fatalities & Injuries	**#/Gwe yr**	0.6	<0.6
Licensability	**[1-3]**	1	3

6.1 Worker Injuries

Azapagic (2013) shows a graph in which she presents the worker injuries for different energy generating technologies in the framework of the UK Spring project. This multidisciplinary research project on sustainability assessment of nuclear power was carried out from 2008 to 2011 and funded by the UK Research Councils in the preparation of new nuclear in the UK. The work shows that CCGT and nuclear have a similar amount of worker injuries of about 6/TWh, which is about one quarter of wind energy, and a tenth of coal and solar energy.

6.2 Evacuees

Burgherr & Hirschberg (2008) present an elaborate study of accidents in the energy production sector. Figure 2 shows a graph in which they present energy related fatalities, injuries, and evacuees. The graph allows extracting values for evacuees related to CCGT and nuclear. For the current KPI assessment, values were extracted for OECD and non-OECD countries. For CCGT the graph shows a value of ~10 evacuees/GWe/yr, whereas for nuclear it shows a value of 257 evacuees/GWe/yr. To these numbers the following remarks should be made.

- The criterion for an accident to be considered as a severe accident taken into account in the assessment of Burgherr & Hirschberg (2008) is that the number of evacuees should exceed 200 people.
- In coal mine accidents evacuations often affect fewer than 200 people, so that an accident is not considered severe according to this criterion. Particularly in some non-OECD countries escape routes in subsurface mines may also become blocked in an emergency due to insufficient safety management of the mines, and thus people may be killed instead of being evacuated or rescued.

- In the natural gas and LPG chains the absolute numbers of evacuees in OECD countries are two orders of magnitude higher than in non-OECD countries due to efficient safety measures and emergency planning, resulting in much higher rates of evacuees per GWe yr, that is, saved lives. Finally, the number of evacuees after a dam failure is strongly dependent on the warning time and the population size downstream of the dam.
- The value for nuclear does not include the evacuees from the 2011 events in Fukushima. It is reported that nearly half a million people who lived within a range of 30 km from the plant were evacuated.

The values presented in the study of Burgherr & Hirschberg (2008) for nuclear refer to all nuclear reactors, but obviously related mostly to light water reactors. For generation 4 reactors, including the HTR, one of the design objectives is that there should be no need for an off-site emergency response. Therefore, in the current assessment and without any statistical data to confirm this design objective, a value of 0 evacuees/GWe/yr is selected.

6.3 Fatalities & Injuries

Within the assessment of Burgherr & Hirschberg (2008), an elaborate overview is presented of fatalities and injuries within the energy production sector. This overview is presented in figure 3 which shows a table of their publication. From this table it becomes clear that the statistics for the different energy production technologies are quite different and lead to complex interpretation. The aggregated and normalized values for fatalities and injuries are presented in figure 2. For CCGT this adds up to about 0.6 persons/GWe/yr. For nuclear the figure is about the same value. However, especially with respect to nuclear a few remarks have been made by Burgherr & Hirschberg (2008).

- Western style nuclear plants have the lowest fatality rates of all energy generation sources.
- In case of the nuclear chain, latent fatalities dominate total fatalities. When one reviews these latent fatalities for the only severe (≥5 fatalities) nuclear accident with an impact on human health (Chernobyl), then estimates of latent deaths would range from 13.9 to 51.2 deaths/GWe/yr (for non-OECD countries). However, extending these risks for nuclear energy to current OECD countries is not appropriate, because OECD plants use other, safer technologies (note that at the time of publication Burgherr & Hirschberg (2008) the Fukushima events which happened three years later were not taken into account). This is also predominantly true for the current situation in non-OECD countries. In the OECD, PSA-based, latent fatalities are therefore generally significantly lower, around 0.02 fatalities per GWe yr (Hirschberg et al. 1998).

Again the question arises as to how to estimate the fatalities and injuries for an HTR. Following the reasoning presented in the previous paragraph, we may assume that the HTR will be safer than current light water reactors and also that no off-site emergency response will be required. Therefore, it is decided to indicate that the fatalities and injuries for an HTR will be lower than the reference value for nuclear, i.e. for an HTR the value should be <0.6 persons/GWe/yr.

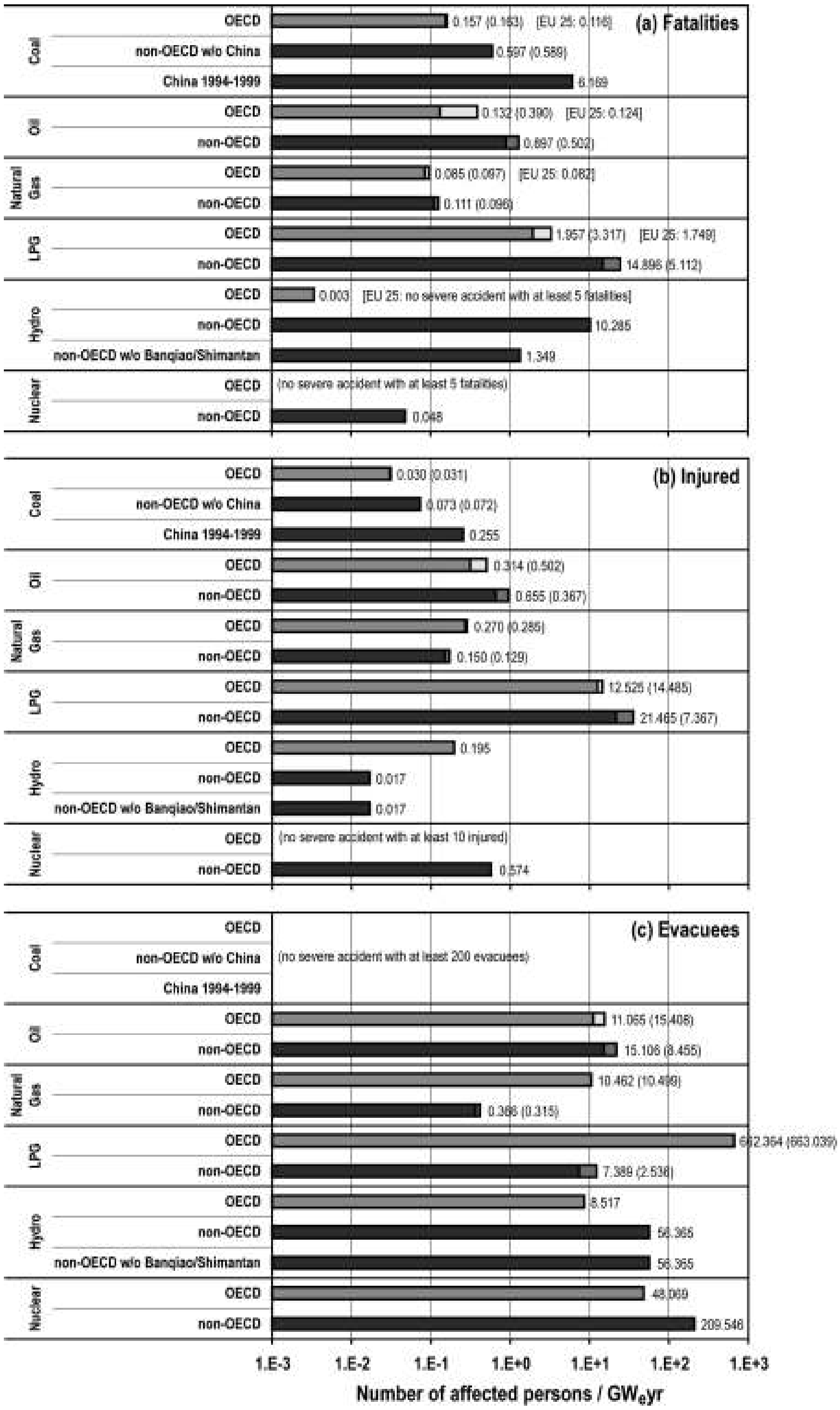

Figure 2: Comparison of aggregated, normalized, energy-related damage rates for (a) fatalities, (b) injured, and (c) evacuees, based on historical experience of severe accidents that occurred in OECD (EU 25 in rectangular brackets for fatalities only) and non-OECD countries in the period 1969–2000, except for coal China where complete data from the China Coal Industry Yearbook were only available for the years 1994–1999 (Burgherr & Hirschberg, 2008).

Summary of severe accidents with at least 5 *immediate* fatalities that occurred in fossil, hydro, and nuclear energy chains in the period 1969–2000. Accident statistics are given for the categories OECD (incl. EU 25), EU 25 alone, and non-OECD. For the coal chain, non-OECD without China and China alone are given separately. Acc = number of accidents, Fat = number of fatalities.

	OECD		EU 25		non-OECD		World total	
Energy chain	Acc	Fat	Acc	Fat	Acc	Fat	Acc	Fat
Coal	75	2259	32	697	102	4831	1221	25107
					1044	18,017		
					(819)[a]	(11,334)[a]		
Oil	165	3713	60	1185	232	16,505	397	20218
Natural gas	90	1043	28	276	45	1000	135	2043
LPG	59	1905	20	564	46	2016	105	3921
Hydro	1	14	0	0	10	29,924[b]	11	29938
Nuclear	0	0	0	0	1	31[c]	1	31
Total	390	8934	140	2722	1480	72324	1870	81258

[a]First line: Coal non-OECD without China; second and third line: Coal China 1969–2000, and in parentheses 1994–1999. Note that only data for 1994–1999 are representative because of substantial underreporting in earlier years (Hirschberg *et al.* 2003a, 2003b).

[b]Banqiao/Shimantan dam failures together caused 26,000 fatalities. [c]Only *immediate* fatalities. In the case of Chernobyl estimates for *latent* fatalities range from about 9000 for Ukraine, Russia, and Belarus to about 33,000 for the whole northern hemisphere in the next 70 years (Hirschberg *et al.* 1998). According to a recent study (Chernobyl Forum 2005) by numerous United Nations organizations (IAEA, WHO, UNDP, FAO, UNEP, UN-OCHA, and UNSCEAR) up to 4000 persons could die due to radiation exposure in the most contaminated areas. This estimate is substantially lower than the upper limit of the PSI interval, which, however, was not restricted to the most contaminated areas.

Figure 3: Summary of energy production related severe accidents (Burgherr & Hirschberg, 2008)

6.4 Licensability

An important aspect for a potential end-user of a cogeneration system will be the licensability of the system. It is decided to indicate this KPI on a scale of 1 to 3 in which 1 means easy to license and 3 means difficult to license. As CCGT plants are currently operating, apparently, licenses could be obtained and therefore for CCGT a value of 1 is selected for this KPI. For HTR, the licensing for a plant in combination with cogeneration has never been shown. Gas cooled nuclear plants (Magnox and AGR's) have been licensed for electricity generation in the UK. Furthermore, a lot of the licensing expertise and knowledge from former HTRs which have been operated in the past has been lost and needs to be retrieved and updated in line with current licensing practises. Next to that, all stakeholders involved in the development of HTR technology, recognise that the lack of a licensing framework for

HTR, together with the licensing process itself, is one of the largest obstacles and risks for HTR technology to become mature. This can for example be demonstrated by the NGNP Alliance, which indicates that the first phase, i.e. licensing, is the most risky one. This phase, in their view, needs to be covered by governmental support, both technically (for establishing the HTR licensing framework) and financially. Therefore, a value of 3 is selected.

7 Economic Assessment

7.1 Top-down Cost Estimate Approach

Cost estimates of future complex technological systems (like a nuclear reactor system) which are only available in a (pre-)conceptual stage are complicated and show large uncertainties. On the other hand, such cost estimates are essential to challenge the justification of the ongoing developments and investments as the economic performance will determine the market potential and penetration of a new nuclear plant design to a large extent, considering the fully competitive deregulated market in which they will have to be built and operated. Most often, such cost estimates are made in a bottom-up approach. The reactor system under consideration is broken down into components and realistic cost estimates are made for each component. However, as the fourth generation nuclear reactor concepts are often in a preliminary stage, a thorough bottom-up cost estimate from component level cannot be made accurately.

In this report, a top-down cost estimate of a future HTR is described. This cost estimating approach has been developed to provide as realistic as possible cost estimates for future nuclear reactor systems and their associated fuel cycles. The approach is based on a comparative analysis using a structured accounting system as applied in the G4Econs model which is developed by Economics Modeling Working Group of the Generation IV International Forum (GIF EMWG). The approach has been described in the article of Roelofs & Van Heek (2011).

The presented top-down cost estimate approach, uses, like most bottom-up approaches, a cost accounting system. This system breaks the reactor system down into small(er) accounts (components) for which cost estimates are to be determined. The International Atomic Energy Agency (IAEA) has developed a comprehensive account system capable of addressing a spectrum of capital, fuel cycle, and operations and maintenance costs, from a complete nuclear energy plant down to individual systems and components (IAEA, 2000). Because this accounting system has a high degree of flexibility, it can be used for all types of reactor systems, single or dual-purpose energy plants, and various contract or deployment approaches. To meet the needs of the EMWG and the system designers/estimators, some revisions were made to the IAEA account system to create the GIF code of accounts (COA). The GIF COA has multiple levels of detail, the first level being the most generic and later levels containing increasing details.

Following the COA provided by GIF/EMWG (2007) the construction costs for the different reactor types are estimated relative to the construction costs of a reference plant which are put to 100%. In this case, a Generation III nuclear power plant is used as a reference plant. Even if no data is available for the separate accounts or ultimately for the overall capital costs of the reference plant, the approach still provides a qualitative inter comparison of different reactor systems.

For the second level of accounts, several references provide the relative distribution of the costs for different reactor types. This indicates to what extent a specific account contributes to the overnight construction costs for a given reactor type. For example, the reactor vessel and other reactor plant equipment may be expected to pay a larger contribution to the overnight construction costs for Generation IV plants than for Generation III plants because of the application of more expensive materials which can withstand elevated temperatures and more demanding coolants.

As a second step in the assessment, using these relative cost distributions based on the second level of accounts, the costs for different accounts are determined relative to the reference plant which is put to 100% using certain assumptions. The third step is to make the comparative analysis. Figure 4 provides an overview of the developed comparative COA based approach. On top, the cost distribution for a (Generation III) reference plant is displayed as segments in a circle. Below this two different Generation IV plants are considered each having different cost distributions and presented as two further circles for comparison. The bullets below the two lower circles represent the individual accounts, showing that the evaluation of these individual accounts may lead to different conclusions for the designs under consideration.

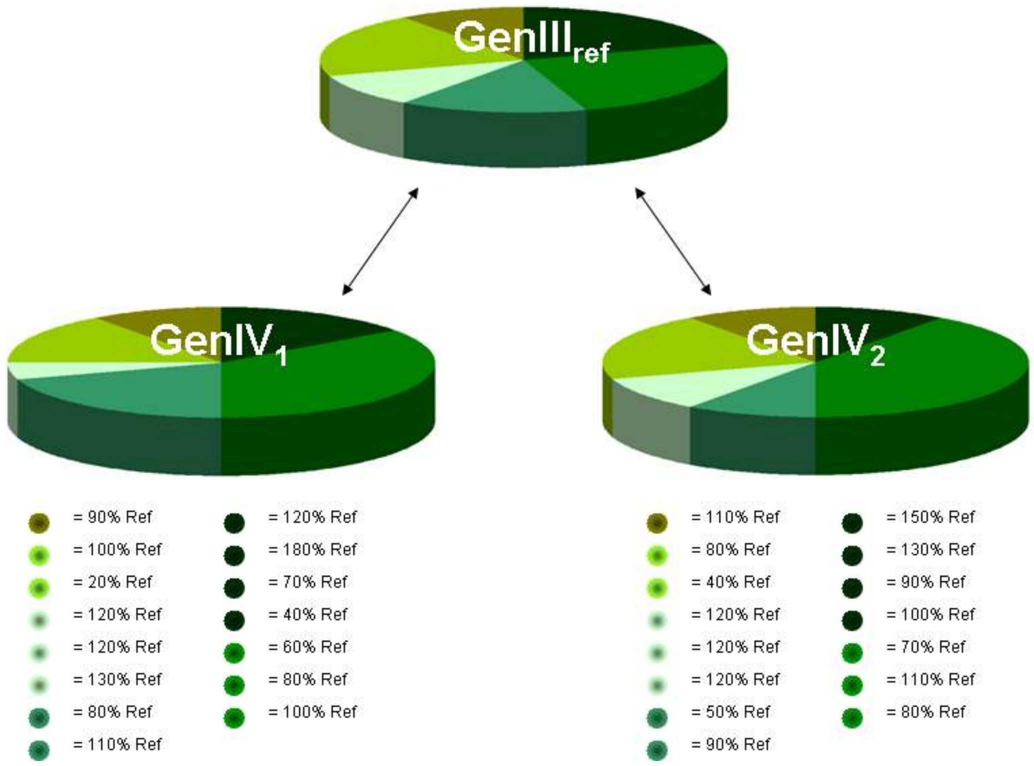

Figure 4: Visualization of the comparative COA based cost estimate approach

The purpose of the current assessment is to estimate construction costs, operation and maintenance costs, the fuel cycle costs, and ultimately the energy generation costs. The information on construction costs is used as input for the general energy generation cost assessment using the G4Econs tool developed by GIF EMWG. This tool uses a similar accounting system for the derivation of costs.

Ultimately, a similar approach was followed here for many of the accounts, i.e. their values were derived mainly by comparing against existing data for a reference system.

7.2 General Assumptions

7.2.1 Inflation

Many of the data are available for a certain date. As currencies change over time and inflation rates are different from country to country, assumptions have to be made with respect to historical inflation rates. All data selected originates either from European or from US sources. Therefore, only the historical inflation rates of the US dollar and the euro have been considered. The US data were derived from the US Inflation Calculator available on internet, whereas the European data were derived from Eurostat. The historical data retrieved are interpolated and fits are made using a constant inflation rate (see figures 5 and 6). The following constant values of the fits are used:

US dollar (1994-2011): 2.5%

Euro (1998-2011): 2.1%

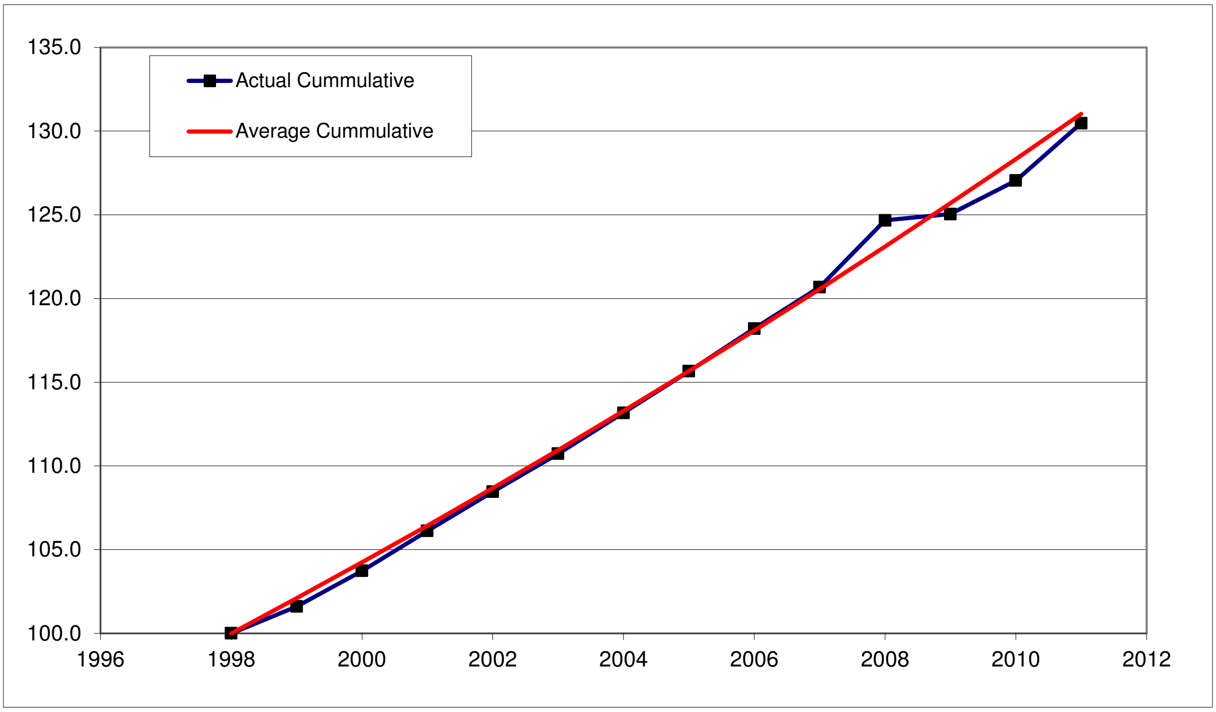

Figure 5: Historical inflation rate of the Euro compared to a fit with 2.1%

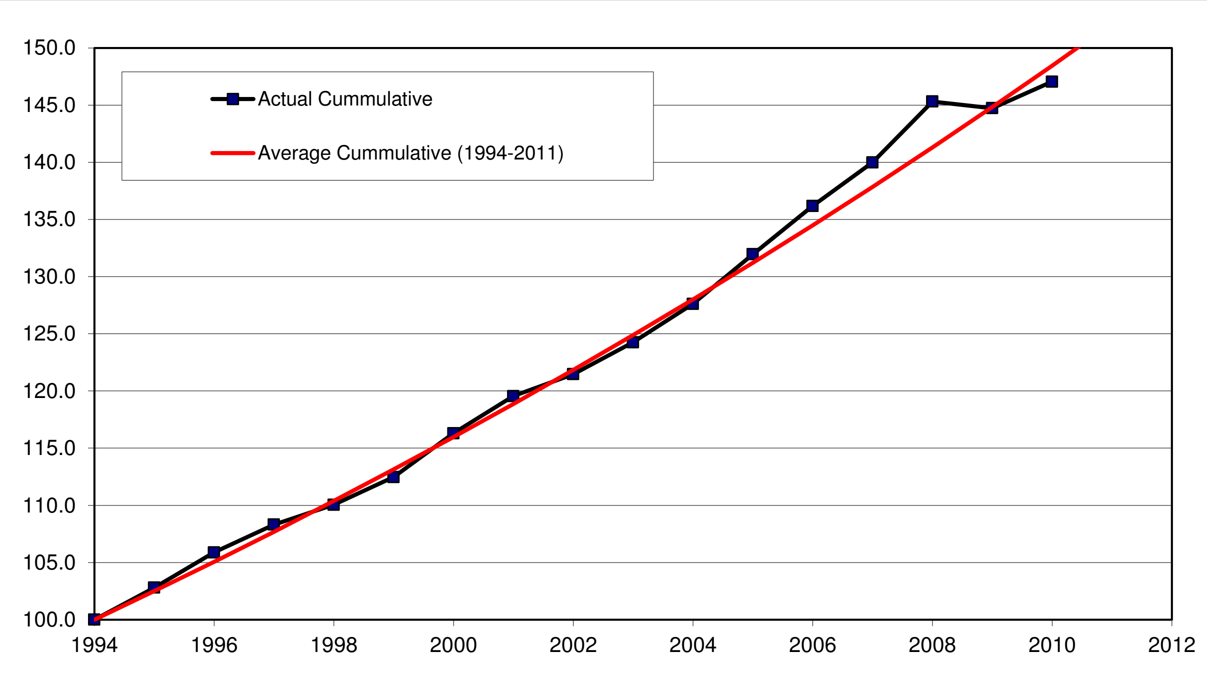

Figure 6: Historical inflation rate of the US dollar compared to a fit with 2.5%

It can clearly be concluded from both figures that the data was fairly constant up to the economic crisis in 2007. After that, fluctuations are observed which are hard to model using a constant value. However, as uncertainties arising from other sources in the current assessment are considered to be of much larger influence, constant values have been used in the current assessment.

7.2.2 Currency Exchange

The main currency exchange required in this document is the currency exchange between the US dollar and the euro. To this purpose, all information in US dollars is first escalated to 2009 values. Therefore, the only currency exchange used throughout the document is the exchange from 2009 US dollar to 2009 euro. As the exact value varies from day to day and the uncertainties in this type of cost estimates is high in any case, a standard value of 1.5 dollars for 1 euro is selected.

7.3 Cost Accounting

A comprehensive account system capable of addressing a spectrum of capital, fuel cycle, and operations and maintenance costs, from a complete nuclear energy plant down to individual systems and components has been developed by the IAEA (2000). Because this accounting system has a high degree of flexibility, it can be used with all types of reactor systems, single or dual-purpose energy plants, and various contract or deployment approaches. The GIF EMWG has adopted this accounting system, however, to meet the needs of the GIF system designers and cost estimators, some revisions were made to the IAEA account system to create the GIF code of accounts (GIF COA). The GIF COA has multiple levels of detail, the first level being the most generic and later levels containing increasing details.

7.3.1 Cost Distribution

At the second level of accounts, a cost distribution between the different main components forms the starting point. This indicates to what extent a specific account contributes to the overnight construction costs for a given reactor type. For example, the reactor vessel and other reactor plant equipment may be expected to pay a larger contribution to the overnight construction costs for Generation IV plants than for Generation III plants because of the application of more expensive materials which can withstand elevated temperatures and more demanding coolants.

The cost distribution for an HTR is based on the assessments of Buda (1986) and Williams (2008) for a cost estimate of the HTR Modul and a cost estimate of the MPBR. Table 2 presents the cost distribution applied for HTR.

Table 2: Assumed cost distribution for a pebble bed HTR

Account	Cost Distribution
Buildings & Structures	14%
Reactor	35%
Turbine	18%
Electric	5%
Miscellaneous	1%
Heat Rejection Systems	4%
Specials	0%
Simulator	1%
Construction Services	13%
Other (Owner costs)	9%

7.3.2 Comparison to Reference Plant

In order to enable a comparative analysis, a reference plant has to be selected. To this purpose, a generic Generation III 1100 MW reference light water reactor with predominantly passive safety features like e.g. the AP1000 reactor design was selected among the various Generation III reactor designs. It should be noted that the separate safety systems may vary significantly from a light water reactor to an HTR, however, it is assumed that this approach will provide a better comparison than using a reactor design that largely bases its safety philosophy on redundancy.

7.3.3 Scaling Relationships

One of the main considerations for each code of account is to scale plant data to the reference plant data with the net electric (or thermal) power. For this, scaling relationships such as presented below can be employed based on the data provided in the Nuclear Energy Cost Data Base provided from Delene et al. (1988).

$$\mathrm{Cost}_{new} = \mathrm{Cost}_{ref} \left(\frac{\mathrm{Power}_{new}}{\mathrm{Power}_{ref}} \right)^{a}$$

In which ‘Cost_{new}’ and ‘Cost_{ref}’ are the costs for the considered plant and the reference plant respectively, ‘Power_{new}’ and ‘Power_{ref}’ are the power levels for the considered plant and the reference plant respectively, and ‘a’ is the scaling factor.

Table 3: Scaling factors (MacDonald & Buongiorno, 2002)

Account	Small Power Difference	Large Power Difference
Buildings & Structures	0.5	0.59
Reactor	0.6	0.80
Turbine	0.8	0.83
Electric	0.4	0.39
Miscellaneous	0.8	1.06
Heat Rejection Systems	0.3	0.59
Construction Services	0.42	0.66

The above scaling relationships account for the fact that smaller systems still require some basic investments and other investments which do not scale linearly with the reactor size. Existing values for the scaling factor are usually only valid for nuclear reactor systems that provide comparable net power. Using such values, MacDonald & Buongiorno (2002) derived scaling factors for systems with large differences in net power. This allowed them to derive a top-down cost estimate for a small modular fast reactor in comparison with a large scale reactor. As HTR and the reference plant employ net powers which almost differ a factor of 5, these values, presented in table 3, for the scaling factor are applied.

7.3.4 Modular Construction

From the reported assessment by Roelofs & Van Heek (2011), it was concluded that the evaluation was largely based on scaling effects. This was considered a large drawback especially when large power differences had to be considered. On the other hand, the benefits of modular building (increased standardisation and faster learning curves), were not taken into account in that preliminary evaluation.

For the current assessment an HTR which employs a relatively low power, the comparative approach was extended by taking into account the benefits which arise from modular construction. The approach followed in the current assessment follows the analysis of Boarin & Ricotti (2011). In their analysis, they separate four effects of modular construction:

1. Learning factor

   The number of similar plants constructed world-wide will lead to increased experience in construction and therefore in decreased costs
2. Modularity factor

   Modularization factor assumes capital cost reduction for modular plants, based on the reasonable assumption that the lower the plant size, the higher is the degree of design modularization
3. Multiple Units factor

   Multiple units saving factor shows progressive cost reduction due to fixed cost sharing among multiple units on the same site
4. Design factor

   The design factor takes into account a cost reduction by assumed possible design simplifications for smaller reactors

Figure 7 shows the curve constructed when all these separate effects are combined. A simplified curve was fitted through this graph requiring only input with respect to the reference plant net power ‘$Power_{ref}$’ and the net power of the plant under consideration ‘$Power_{new}$’. As shown in the graph, this simplified curve is only valid for reference plants in the range of 600-1800 MWe. The simplified equation for the modular construction factor (mcf) reads:

$$\mathrm{mcf} = \min\left(0.195 \ln\left(\frac{Power_{new}}{100}\right) + 0.63 \cdot 10^{-4} Power_{ref}\ ; 100\%\right) \qquad (1)$$

Application of this equation to the HTR in comparison with the reference plant leads to a modular construction factor of 66%.

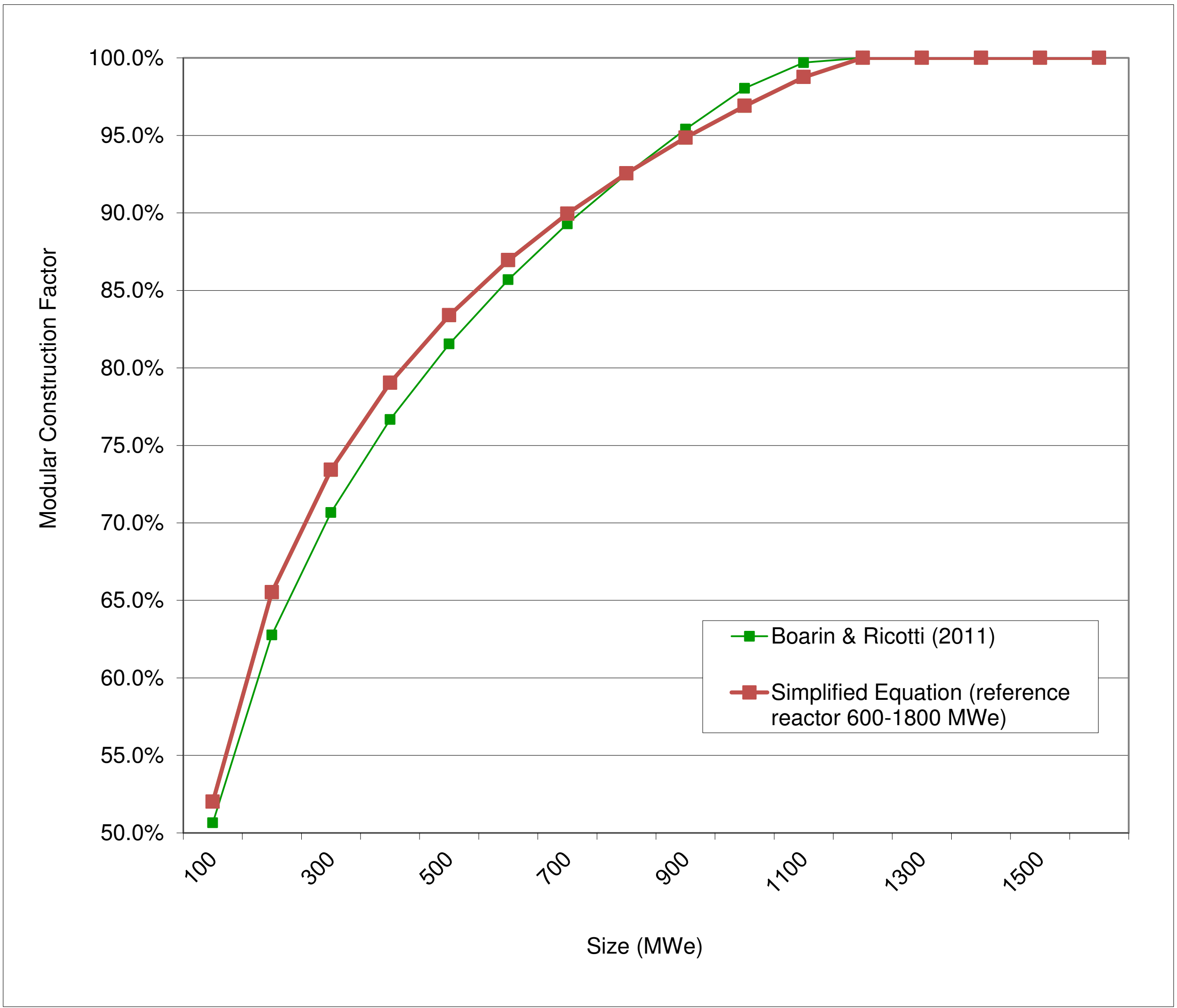

Figure 7: Modular construction factor

7.3.5 Main Assumptions

Apart from application of scaling factors and the modular construction factor as described above, the following main assumptions have been applied:

- Site size
  Freis (2013) provide a plot plan for the reference HTR which shows a total plot area of 240m by 170m which equals 41000 m^2. As a comparison, the plot plan of the AP1000 is considered. In Westinghouse (2007), it says that the Concrete Shield Building has an inner diameter of about 140 feet (43 m), a height of 73.25 ft (22 m), and a wall thickness of 3 ft (0.9 m) in the cylindrical section. With this information, and the plot plan from IAEA (2011), a site area length of 243 m and site area width of 187 m can be derived, resulting in a site area of about 45000 m^2.

- Reactor plant equipment
  The HTR plant described by Freis (2013) consists of two reactors. Therefore, after taking into account appropriate scaling (see paragraph 7.3.3), the values have to be multiplied by two.
  - Reactor equipment
    It is assumed that an HTR vessel resembles the vessel of a typical boiling water reactor. OECD/NEA (2000) provides cost estimates for a European Pressurized Reactor (EPR) and an Advanced Boiling Water Reactor (ABWR). Carefully processing these data, one may arrive at a cost estimate for a typical BWR to be about 60% of the EPR. However, the reference light water reactor in the current assessment is an 1100 MWe reactor. When taking the appropriate scaling into account, one arrives at the costs of an HTR reactor vessel to be about 80% of the reference Gen III reactor.
  - Fuel handling system
    With respect to the fuel handling system, after scaling a factor of 1.5 was applied in order to take into account the complex pebble fuel handling machines which will require a special design and will be used extensively.
  - Safety systems
    As explained before, it is assumed that both reactors share a similar approach in designing as much as possible passive safety systems. Therefore, also similar costs are taken into account.

7.4 G4Econs Assessment

7.4.1 G4Econs Tool

G4Econs (**G**eneration **4 E**xcel **C**alculation of **N**uclear **S**ystems) is an Excel based nuclear fuel cycle simulation tool (GIF/EMWG, 2008) developed by the Economic Modelling Working Group (EMWG) of the Generation IV International Forum (GIF). Apart from the elaborate description by GIF/EMWG (2008) and the cost estimating guidelines provided by GIF/EMWG (2007), a short description of the tool can be found in Williams (2007). The tool allows to calculate levelised unit electricity costs by taking into account design characteristics, fuel characteristics, the associated fuel cycle and it's costs, the O&M costs broken down in a code of accounts, the capital costs broken down in a code of accounts, financing costs, and contingencies.

In the application of G4Econs, a range of values for every account can be specified by providing an optimistic, nominal, and pessimistic value. This feature has been used to calculate ranges for the construction, operation & maintenance, fuel cycle, and electricity generation cost. Optimistic, nominal, and pessimistic values were specified for most reactor characteristics, O&M accounts, and fuel cycle costs. The range was determined by selecting for all accounts either the optimistic values or the pessimistic values.

7.4.2 Main Assumptions

- **Construction Costs**
  The construction costs are adopted from the COA based approach described in the previous chapter. As both tools are based on the same set of accounts, the transition can be made fairly easy. It should be noted that an important assumption is made concerning the research and development (R&D) costs. No R&D costs are taken into account. It is recommended to estimate these in a future assessment. Furthermore, the D&D costs are included in the construction costs. Following the recommendation of GIF/EMWG (2007), these costs are considered 1/3 of the construction costs.
- **Operation & Maintenance Costs**
  The operation and maintenance costs within G4Econs are separated in a number of accounts. The values used for HTR are largely based on the assessment of Fischer (1999) for the EPR and scaled with net reactor power. For an estimate of the permanent staff, the equation derived in Roelofs et al. (2011) is followed. This shows that the number of permanent staff for the HTR would be about 25% compared to the EPR. For the consumables, an estimate is made that the costs will be about 20% more than for a contemporary LWR because of the more expensive materials and components needed to deal with elevated temperatures. For repair costs it is assumed that it should be similar to a contemporary mostly passive LWR.
- **Fuel Cycle Costs**
  The fuel cycle costs are based on the costs provided in the Advanced Fuel Cycle Costs Database published by Shropshire et al. (2009). This database does not provide costs for the manufacturing of fuel pebbles such as those used in the HTR plant described by Freis (2013). These data were obtained from Maddalena (2001).
- **Contingencies**
  Assuming contingencies are not taken into account in the literature values (e.g. for the determination of the construction costs of the reference power plant), an overall contingency of 25% has been taken into account in the present assessment reflecting the current development stage of the HTR.
- **Other Main Assumptions**
  - For the interest during construction a discount rate of 10% is assumed.
  - The HTR is assumed to have a 42% electric efficiency when used for production of electricity only (see also paragraph 5.4). This is based on the efficiency considered for HTR-PM used for electricity production only as provided by Zhang et al. (2009) which may be on the low side providing a conservative evaluation. When cogeneration is considered, the values provided by Freis (2013) are taken, i.e. 127 MWe in combination with 400 t/hr process heat.
  - Relevant core, fuel, and refuelling data are obtained from Freis (2013). Spent fuel compositions are taken from Haas & Kuijper (2003).
  - Insurances and taxes have been taken into account as 0.45% of the (pre-)construction costs as recommended by GIF/EMWG (2007).

7.5 Cost Estimate

7.5.1 Engineering, Licensing & Construction Costs

To determine the specific construction costs of the HTR, firstly the specific construction costs of the reference plant need to be determined. A reference 1100 MW Third Generation LWR design with predominantly passive safety features was selected for this purpose and a number of recent authorative sources were consulted. Table 4 summarizes the literature review results. The table also provides the value of 3200 €/kWe which was selected as the reference costs for a generic 1100 MW Gen III reactor for the current analysis.

Table 4: Gen III construction costs from literature

Literature source	Generic Gen III specific construction costs
Keystone (2007)	2400 €/kWe
Standard & Poor (2008)	3200 €/kWe
Tarjanne (2008)	2900 €/kWe
MIT (2009)	3200 €/kWe
OECD/NEA (2010)	3300 €/kWe
1100 MW Gen III	**3200 €/kWe**

Compared to the assumed generic 1100 MW Gen III reactor construction costs as reported in literature, applying scaling relationships, considering benefits of modular construction as described earlier, and considering the main assumptions described above, the nominal HTR construction costs were found to be about 40% higher and are determined at 4500 €/kWe. Figure 8 presents the construction costs range as determined within the G4Econs assessment against the nominal.

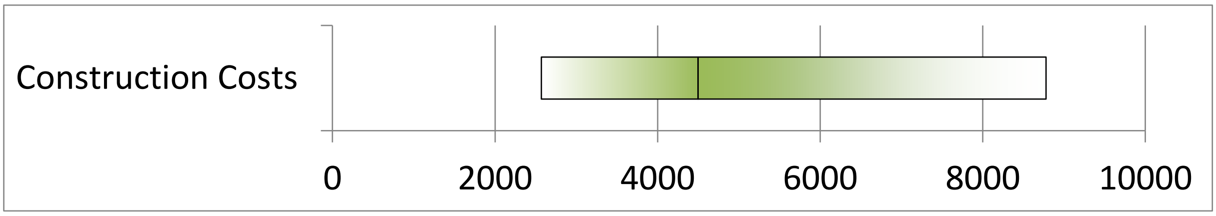

Figure 8: HTR engineering, licensing & construction costs [€/kWe]

7.5.2 Operation & Maintenance Costs

The operation and maintenance costs as determined from the G4Econs assessment are depicted in figure 9. The nominal value is 90 €/kWe/a. For comparison, typical recently published operation and maintenance costs for a generic light water reactor plant are considered in the range of 34 to 78 €/kWe/a. This shows that for an HTR plant the expected operation and maintenance costs are considerably higher than for a light water reactor plant. This is mainly because of the relatively small scale of the reactor.

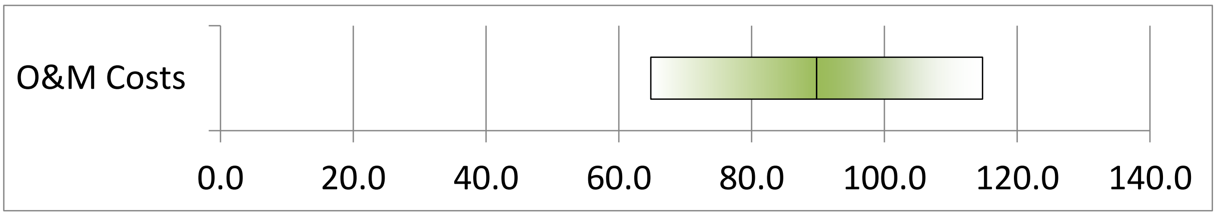

Figure 9: HTR operation and maintenance costs [€/kWe/a]

7.5.3 Fuel Cycle Costs

The fuel cycle costs as determined from the G4Econs assessment are depicted in figure 10. The nominal value is 7.7 €/MWh. Typical values for a light water reactor are in the range of 6 to 17% of the energy generation costs (OECD, 2005). Assuming energy generation costs of about 60 €/MWh (MIT, 2009) for a typical Third Generation light water reactor, this would correspond to a range of about 3.5 to 10 €/MWh which covers the larger part of the range calculated for the HTR.

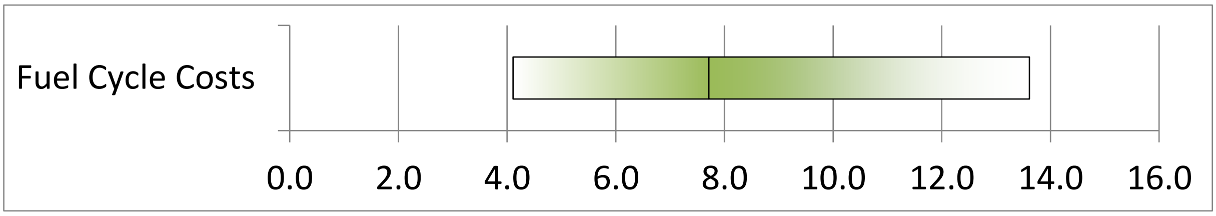

Figure 10: HTR fuel cycle costs [€/MWh]

7.5.4 Energy Generation Costs

The G4Econs tool eventually allows to calculate the energy generation costs for a reactor system and its associated fuel cycle. For the HTR, this sums up to energy generation costs with a nominal value of about 120 €/MWh. The complete range is presented in figure 11. This is high compared to the value given for contemporary light water reactors in MIT (2009) which is about 60 €/MWh. It should be noted that such values are very sensitive to the interest rate during construction. Nevertheless, this clearly indicates that application of a small modular HTR as electricity only generator is not more economic than application of conventional light water reactors. This has been confirmed by Western nuclear vendors. On the other hand, economic competitiveness of an n^{th}-of-a-kind HTR producing electricity only compared to existing light water reactor, is claimed by INET, currently responsible for the development and licensing of the HTR-PM plant in China. This may be correct for China, where construction costs may be significantly lower.

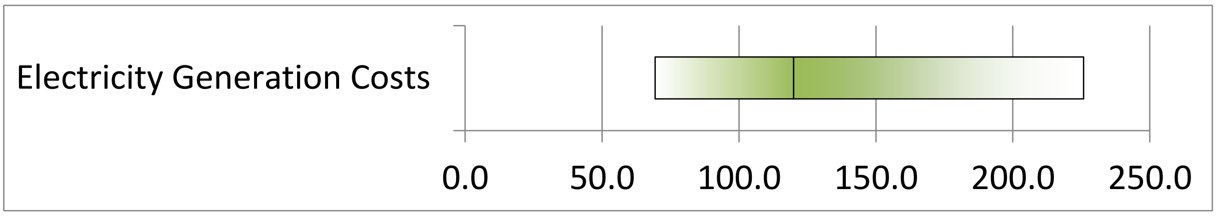

Figure 11: HTR energy generation costs for a electricity only producing plant [€/MWh]

7.5.5 Electricity Only v.s. Cogeneration

Within G4Econs also the economics of a nuclear heat source coupled to a heat application can be evaluated. To this, the main assumptions needed are for the heat application. In the current case, it is assumed that the HTR will be placed in a plug-in market. This means that the steam infrastructure is already present at the site. Therefore, the additional systems needed to couple the nuclear heat source to the process heat application are limited. To estimate these costs, the following is assumed. The heat exchangers needed to couple the process heat application to the nuclear heat source should be taken into account and additional provisions may be considered for a tritium cleaning plant if needed. The total costs for this are estimated against the costs of 3 intermediate heat exchangers. Gandrik (2012) shows that the costs for an intermediate heat exchanger are similar to the costs of a heat rejection plant. As these costs were already considered in the cost estimate of the HTR plant as described in paragraph 7.3, the application costs could be estimated and are relatively low, i.e. 1.0 €/MWh.

The G4Econs tool starts with evaluating the level of thermal power produced and which part has to be put into the process heat system. From this, it becomes clear as to how much thermal energy is left to produce electricity. Once this is known and the costs of the nuclear heat source are calculated as specified in paragraphs 7.5.1 through 7.5.4, the levelized unit electricity costs (electricity generation costs) can be calculated. The levelized unit product costs (process heat generation costs) should be added to this.

In order to obtain an impression of the benefits of cogeneration, the G4Econs assessment has been extended to include an evaluation of the income generated from both electricity sales and process heat sales. Following Gandrik (2012), the ratio of process heat to electricity price to industrial users is assumed to be 0.43. A realistic wholesale or industry electricity price in Europe can be obtained from www.energy.eu and this equals about 100 €/MWh. When an HTR is used to produce electricity only, this will result in total revenues of about 108 M€/yr. The costs on the other hand can be calculated from paragraph 7.5.4 to be 202 M€/yr. It is clear that the revenues in this case are not sufficient to cover the costs. However, when in addition process heat is sold, the revenues increase depending on the assumed ratio between electricity price and heat price, whereas the costs only increase marginally to about 206 M€/yr. A break-even point is reached at a ratio of about 0.65. At a higher ratio, the cogeneration plant is profitable. This clearly shows the benefits of using an HTR for both electricity and process heat. In fact, it suggests that an HTR needs to be applied with cogeneration in order to become economically viable.

A sensitivity analysis on the break-even ratio of heat and electricity price for the ARCHER HTR system is shown in figure 12. This study reveals that there is a lower boundary of the break-even ratio of heat and electricity price which is around 0.6 in this specific case. Increasing the ratio between process heat and electricity does not lead to a lower break-even ratio.

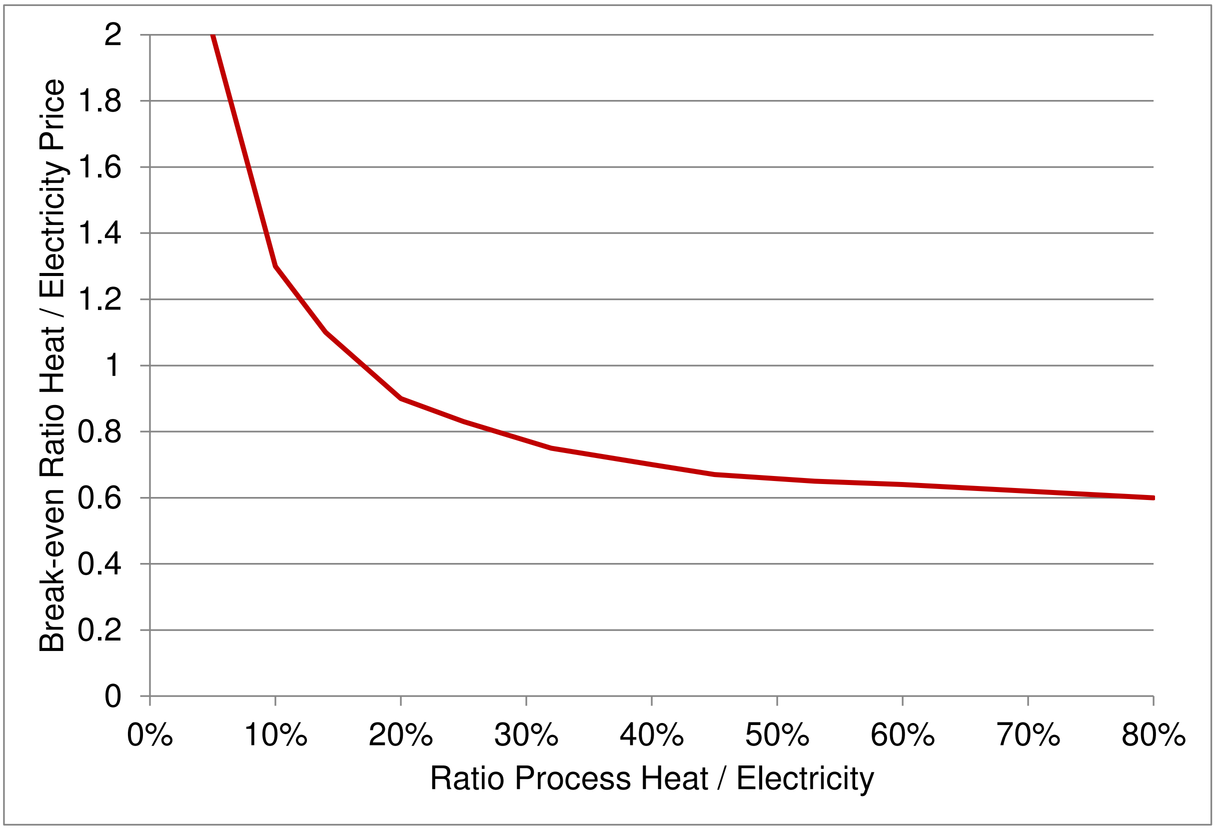

Figure 12: Break-even ratio of heat and electricity price related to the ratio of process heat to electricity.

8 Economic KPIs

KPI	Unit	Gas Fired Plant	HTR
Construction Costs	**€/kWe**	550	4500
O&M Costs	**€/kWe/yr**	28	90
Fuel Cycle Costs	**€/MWh**	65	8
Decommissioning Costs	**€/kWe**	~0	650
Generation Costs	**€/MWh**	150	150

8.1 Construction Costs

Construction costs for the HTR have been determined using the top down cost estimate approach explained in chapter 7. Paragraph 7.5.1 shows that this approach results in an estimate of about 4500 €/kWe. The construction costs of a CCGT plant are taken from Locatelli & Mancini (2010) which provide a value of 550 €/kWe. This value is based on their review of construction costs for actual plants taking into account European countries and escalating all the values to the reference year used in the current report (2009). It is clear, and well known, that the construction costs of a nuclear plant are much higher than that of a CCGT plant.

8.2 Operation & Maintenance Costs

Operation & maintenance (O&M) costs for the HTR have been extracted from the G4Econs assessment explained in chapter 7. Paragraph 7.5.2 shows that this approach results in an estimate of about 90 €/kWe/yr. The O&M costs of a CCGT plant are taken from Locatelli & Mancini (2010) which provide a mean value of 24 €/kWe/yr. This value is based on their review of O&M costs for actual plants taking into account European countries and escalating all the values to the reference year used in the current report (2009).

8.3 Fuel Cycle Costs

Fuel cycle costs for the HTR have been extracted from the G4Econs assessment explained in chapter 7. Paragraph 7.5.3 shows that this approach results in an estimate of about 8 €/MWh. The fuel cycle costs of a CCGT plant are taken from Locatelli & Mancini (2010) which provide a mean value of 65 €/MWh. This value is based on their calculations and again escalating the value to the reference year used in the current report. It clearly shows that the fuel cycle costs are the determining cost factor for CCGT. Whereas, for nuclear the fuel cycle costs contribute marginally to the total energy generation costs.

8.4 Decommissioning Costs

Locatelli & Mancini (2010) provide a value 830 €/kWe for a 335 MWe small nuclear light water reactor. In the current assessment, it is assumed that the decommissioning costs of an HTR will employ the same order of magnitude. However, the power difference between the two systems has to be taken into account. This can be done using a scaling relationship as explained in paragraph 7.3.3. The scaling factor derived from the values in tables 2 and 3 for the overall system is about 0.56. Applying this in the scaling relationship, the decommissioning costs for the HTR are determined at 650 €/kWe.

8.5 Generation Costs

The IEA/OECD (2010) provide electricity generation costs at different discount rates for various regions in the world. Figure 13 shows the results of their evaluation of the ranges of electricity generation costs at 5% and 10% discount rates. It is apparent that at a 5% discount rate, nuclear is far more attractive than at a 10% discount rate. Furthermore, one may derive from this figure that with a discount rate near 10% (which is assumed in the rest of the current KPI assessment), the electricity generation costs for nuclear and CCGT are similar and around 100 US$/MWh. Taking into account the exchange rate in the reference year (2009), this would convert to about 150 €/MWh. This value is selected for the current KPI evaluation for both systems. The order of magnitude for nuclear is well within the range of values resulting from the G4Econs assessment for HTR, which shows a nominal value of ~120 €/MWh.

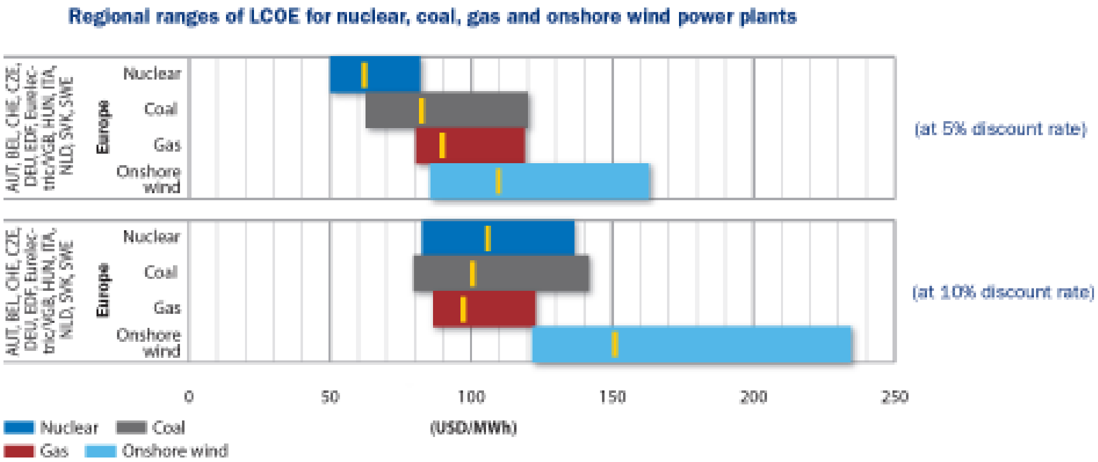

Figure 13: European ranges of electricity generation costs for different discount rates (IEA/OECD, 2010)

9 Conclusions

Within the current assessment, a number of key performance indicators are defined as a basis for comparison between HTR cogeneration and a reference gas-fired cogeneration plant. The purpose is to to identify pathways towards improved emloyment of HTRs, specifically with respect to the performance when being used for cogeneration.

To this purpose, a summary of the KPI assessment is provided below per category:

- Plant characteristics
  The plant characteristics are selected such that the CCGT plant and the HTR plant are to a large respect very similar, i.e. with respect to the power level, the availability, the plant life time, and the space requirements. Obviously, differences are found in the time to market and the construction duration.
- Environmental KPIs
  The assessment shows that when waste is considered, the HTR system produces more radioactive waste. With respect to all other forms of waste, the HTR produces less to much less waste. Typically, radioactive waste is associated with very long lifetimes. This cannot be neglected. However, one should realize that some of the conventional or chemical waste will never be taken out of the environment and will always remain dangerous to living creatures. Where to put more emphasis is not so much a technical issue, but rather a political question. Further quantification with regard to the economic parameters associated with external costs are also provided and from a technical-economic point of view a nuclear system would have the preference.
- Safety KPIs
  With respect to safety a comparison based on actual facts is hard to achieve as statistics are lacking for nuclear, let alone for an HTR. If the HTR system will be able to fulfil its promising safety characteristics, the HTR system might be a little safer than a CCGT which as such is relatively safe when compared to many other forms of energy generation. A rather different aspect of safety is the licensability. For HTR, the licensing of a plant in combination with cogeneration has never been shown. Furthermore, much of the licensing expertise and knowledge from the HTRs which have been operated has been lost and needs to be retrieved and updated in line with current licensing practises.
- Economic KPIs
  The economic assessment leads to some obvious conclusions that nuclear is expensive with respect to the construction costs and therefore is very sensitive to the interest rate during construction. On the other hand the operation and maintenance costs and the fuel cycle costs are relatively low. When the energy generation costs are considered for plants which only produce electricity, one can show that the costs for both CCGT and nuclear are comparable at a discount rate of around 10%. When lower discount values are considered, nuclear becomes more attractive, on the other hand, when higher values are considered, CCGT becomes more

attractive economically. Further, it is shown that the energy generation costs for an HTR employed with cogeneration in a plug-in market will approximately be of the same order of magnitude as CCGT. However, the assessment has also shown that when the costs are compared to the benefits, i.e. the prize of the energy (electricity and process heat) sold to the market, it becomes clear the the HTR is only viable when it is employed in combination with cogeneration and will not be economically attractive as an electricity only production facility. It should be noted that this situation may vary with respect to the country where the HTR system is foreseen. In this assessment, no attempt has been made to identify components which are critical with respect to their costs in order to determine where major cost reductions could be achieved. For such an evaluation, a bottom-up cost estimating approach would be more suitable.

It has been attempted within the current KPI assessment, to provide an objective overview of the different indicators important for decision makers. As already said, it is clear that the decision to construct an HTR or another energy generation facility is not only a technical one, or a question of economics, but also highly influenced by public opinion and political feelings of the time. Therefore, it is impossible to draw firm conclusions. However, some generic conclusion may be drawn:

- An HTR system can be considered economically viable in Europe when it is employed for the production of electricity and process heat.
- A demonstration of an HTR with cogeneration will be a very important step, as it will remove the current uncertainties associated with licensing and time to market.
- The environmental impact of an HTR is minimal, as long as the safety features claimed are true.
- There seems to be a lower boundary of the break-even ratio of process heat and electricity price. In the current assessment this value is about 0.6 which means that the price for process heat should be at least 60% of the price of electricity for a coupled system to become profitable. However, for other input parameters, other values may be obtained.

10 References

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