Environmental impact assessment of the Molten Salt Reactor (MSR) compared to the Pressurized Water Reactor (PWR) and offshore wind power

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Abstract

The environmental impacts associated with nuclear energy generation have had a direct adverse effect on investments and policy decisions regarding nuclear power development. Most important are the "Top 4" environmental impacts of nuclear waste production, reactor safety, nuclear weapons proliferation and cost of electricity.

Because of their importance to nuclear power development this research assesses the expected environmental impacts of the innovative Liquid Fluoride Thorium Reactor (LFTR) technology, a type of Molten Salt Reactor (MSR) that is expected to exhibit very different environmental impacts from conventional nuclear reactors.

The environmental impacts were assessed based on the Environmental Impact Assessment (EIA) framework and compared to the environmental impacts of conventional nuclear power represented by the Pressurized Water Reactor (PWR), and large scale offshore wind energy as a benchmark of sustainable energy generation.

Overall the Environmental Impact Assessment indicates that the LFTR is expected to perform much better than the PWR in terms of environmental impacts. Wind power is the most sustainable option, but the LFTR leans considerably towards wind's environmental impact profile compared to the PWR.

Performance is especially good for the "Top 4" impacts. The volume of nuclear waste produced is 35x less than in the PWR and 99.99% of the waste that is produced reaches stable natural uranium levels within 300 years. Reactor safety has improved to the point where meltdown and steam explosion can be considered irrelevant and the accidents that can occur are much less severe. The reactor has a strong inherent resistance to nuclear weapons proliferation. Although theoretically possible, it is very difficult to use a LFTR for nuclear weapons production and parties with that intention are likelier to opt for an easier path. Although too early to say for certain, there are indications that cost of electricity will be strongly reduced as well.

Acknowledgements

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List of acronyms and abbreviations

AWEA	- American Wind Energy Association
BBC	- British Broadcasting Corporation
BWR	- Boiling Water Reactor
CO2	- Carbon dioxide
dB	- Decibel
EIA	- Environmental Impact Assessment
EWEA	- European Wind Energy Association]
Fig	- Figure
g CO2 eq/kWhe	- CO2 equivalent per kWh of electricity
GW	- Gigawatt
HAWT	- Horizontal Axis Wind Turbine
IAEA	- International Atomic Energy Agency
IPCC	- Intergovernmental Panel on Climate Change
ITU	- Institute for Transuranium Elements
LFTR	- Liquid Fluoride Thorium Reactor (Pronounced: Lifter)
LWR	- Light Water Reactor
m	- Metre
MIT	- Massachusetts Institute of Technology
MSR	- Molten Salt Reactor
MW	- Megawatt
MWe	- Megawatt of electricity
NERI	- National Environmental Research Institute
NPT	- Non Proliferation Treaty
NRC	- Nuclear regulatory commission
PCS	- Power Conversion System
PWR	- Pressurized Water Reactor
RWE	- Rheinisch-Westfälisches Elektrizitätswerk
UCS	- Union of Concerned Scientists
UN	- United Nations
UNEP	- United Nations Environment Programme
USEIA	- United States Energy Information Administration
VAWT	- Vertical Axis Wind Turbine
EIA Guidelines	- Guidelines for the Environmental Impact Report Second Nuclear Power Plant Borssele
Euratom	- European Atomic Energy Community
FliBe	- Molten salt mixture of lithium fluoride and beryllium fluoride (LiF-BeF2)

1. Introduction

1.1. Background

1.1.1. Sustainable energy challenges

The looming threat of climate change has prompted the world to look for alternative low carbon sources of energy (IPCC, 2007) (Zwiers, et al., 2011) (UCS, 2014). These come in the form of wind, solar, water, geothermal, and biomass based solutions that have exhibited promising results, but it remains uncertain whether they will prove capable of producing energy in such quantities that they can substitute fossil fuels on the scale required to thwart global warming (Greenhalgh & Azapagic, 2009) (UNEP, 2012) (Rijksoverheid, 2014) (UN, 2014). While a formidable task in developed nations, this could be an even greater challenge in developing countries (Hargraves & Moir, 2010) (Cao & Bluth, 2013) (Economist, 2014).

1.1.2. Nuclear energy challenges

Nuclear power is a low carbon energy source (Warner & Heath, 2012) that can generate energy on a very large scale and could make a substantial contribution to meeting energy needs, but is controversial because of the negative characteristics associated with it (Greenpeace, 2006) (Hargraves & Moir, 2010).

The most important negative characteristics mentioned in the literature are the "top 4" problems of *safe long term storage of nuclear waste*, *reactor safety*, *potential for nuclear weapons proliferation*, and the *relatively high costs of nuclear electricity* (MIT, 2003) (Adamantiades & Kessides, 2009) (Greenhalgh & Azapagic, 2009) (Ahearne, 2011) (Teravainen, et al., 2011). These issues carry such weight that they have had a direct influence on (national) policy decisions regarding the development of nuclear energy. This impacts nuclear technology developing companies and other investors in nuclear power because a political decision to abandon or move away from nuclear energy means reduced market potential for new nuclear build, making nuclear technology's long development trajectories a risky investment proposition [1] (Adamantiades & Kessides, 2009) (Greenhalgh & Azapagic, 2009) (Ahearne, 2011).

1.1.3. Potential solutions: the Molten Salt Reactor (MSR)

New innovative forms of nuclear energy technology termed "Generation IV reactors" are currently under development that aim to improve reactor designs to overcome historical issues (World Nuclear Association, 2014). One of these is the Molten Salt Reactor (MSR),

[1] For a full discussion of the effects these issues have had on national policy see appendix A.

a design that departs radically from traditional reactor designs by utilising liquid instead of solid fuel, which is expected to give it significant advantages. When coupled with the thorium instead of the traditional uranium fuel cycle these advantages become even more pronounced and result in a design that is expected to show significant improvement in radioactive waste production, reactor safety, energy efficiency, proliferation resistance, fuel availability, and costs. There is consensus that the MSR will be technologically feasible but a significant amount of research is still required and a demonstration reactor can be ready in around 10 years (Hargraves & Moir, 2010) (Serp, et al., 2014) (Olson, 2011).

While the impact of nuclear reactors on their environment has been shown to be important to the nuclear technology that has been with us for decades, it is arguably even more important to new forms of nuclear technology like the MSR whose unfamiliarity could induce suspicion and fear (Verhagen, 2011, p. 11).

1.2. Aims & objectives

The purpose of this research is therefore to provide a transparent and comprehensive overview of the MSR's[2] expected environmental impacts with the aim of mitigating doubts and fears stakeholders may have, as well as identifying where weaker aspects exist in the design and what their proposed solutions are.

To be able to evaluate what these impacts mean in the context of low carbon energy generation methods, they will be compared to the environmental impacts of conventional nuclear power generation, as well as large scale offshore wind energy as a benchmark of renewable energy generation.

The objectives were defined as:

1. Develop a suitable framework for assessing the MSR's environmental impacts
2. Populate the framework using information from the literature complemented with expert testimony
3. Assess conventional nuclear power and wind energy's environmental impacts from existing literature
4. Compare the three technologies using a suitable evaluation method

[2] Specifically: the Liquid Fluoride Thorium Reactor (LFTR) MSR type

1.3. Novelty

This research offers a methodical approach to identification and initial assessment of what can be expected from a promising new nuclear energy technology's environmental impacts.

Bringing the information on potential environmental impacts together from dispersed sources of literature into one comprehensive overview and filling information gaps is an important step towards understanding the negatives so the positives may become easier to accept.

The research could be valuable to (political) decision makers and potential investors in MSR technology.

Political decision makers can influence nuclear power development and can use this report to inform themselves and their constituencies of the MSR's expected environmental impacts. Potential investors in MSR technology can use this report to learn about the MSR's expected environmental impacts and to help inform predictions on expected future government positions on MSR technology.

The information in this report can also be used to inform the general public.

1.4. Report structure

This introduction is followed by a description of the **methodology** used to achieve the aims and objectives in an academically valid and reliable manner, and **limitations** to this research. That concludes the introductory sections after which the preliminary Environmental Impact Assessment (EIA) of the MSR begins.

The EIA consists of two sections, as suggested by the EIA guidelines[3]: the first is the **"Planned activity"** section which provides background information useful for understanding the three technologies and where their environmental impacts originate from, as well as **alternative** approaches to these three technologies.

The second is the **"Environmental effects"** section which explains the environmental impacts that result from the technologies' characteristics. This section's chapters consist of summaries containing the most important information, in order to provide a quick impression of the impacts without having to cover all of the details. For some of the chapters more detailed explanatory information can be found in appendix G and H if the reader requires more information about a particular impact.

Because of the way the EIA guidelines recommend structuring these two sections, there may be a small amount of overlap between the planned activity and environmental effects sections, but this was kept to a minimum and should not impact evaluation.

As the EIA is populated entirely from various sources of literature and expert interviews, no separate literature review section is included in the report.

While all "environmental effects" categories were subjected to scoring, only the "planned activity" chapters that lent themselves to scoring, and were not discussed in the environmental effects chapter were scored. These are: Nuclear fuel cycle, Transport, Construction, and Decommissioning.

Following the EIA the impacts are evaluated using impact matrices, after which conclusions are drawn and findings discussed.

[3] Guidelines for the Environmental Impact Report Second Nuclear Power Plant Borssele, see methodology

2. Methodology

2.1. Model

The environmental impacts of the MSR, conventional nuclear power, and large scale offshore wind energy were assessed using the internationally accepted Environmental Impact Assessment (EIA) model as a template (Morgan, 2012, p. 5). Using the EIA framework provides reassurance that no potential impacts have been left out to paint a rosier picture in favour of MSR technology and increases research validity.

The model was adjusted to fit this research: EIA is used to assess the environmental impacts of a *specific* planned development so that these may be mitigated (or the project abandoned) if they are very damaging. The purpose of this research is to assess the MSR's expected environmental impacts in *general* because there is no actual reactor planned for a specific location yet.

EIA's for specific developments incorporate many elements that only apply to that particular location, making the outcomes of the EIA relevant to a relatively limited amount of similar locations (local nature, water access, soil properties, landscape, etc.). Because of this, purely site specific EIA items were left out of the discussion.

The literature showed that although EIA is considered the best available method, there still is considerable critique of the way EIA is performed in many cases[4] (Benson, 2003) (Jay, et al., 2007) (Morgan, 2012), with Benson going as far as calling for a drastic reconsideration of EIA itself in favour of new methods (2003, p. 265). It was therefore important to take note of common mistakes and bad practice to avoid repeating past mistakes.

The Dutch system is commended in the literature as an example of relatively good EIA practice (Glasson, et al., 2012, p. 48). Benson (2003, p. 263) mentions that the Dutch system exceeds the minimum provisions of the European Union's Directive 97/11/EC on EIA practice in regarding participation and independent quality control. This is performed by an external EIA Commission[5] and courts are known to have placed high significance on their statements (Polonen, et al., 2011, p. 124).

Best practice as described in the EIA literature was found to be well represented in the "Guidelines for the Environmental Impact Report Second Nuclear Power Plant Borssele" (hereinafter referred to as the **"EIA guidelines"),** a document from 2010 by the Dutch

[4] The reason for not using the UK system was that it "…was the weakest in an international spectrum of mature and embryonic systems." According to Benson (2003, p. 263).
[5] Commissie voor de milieueffectrapportage

ministry of housing, Spatial planning and the Environment, outlining precisely what should be included in the EIA for the planned “Borssele” nuclear power plant.

It resulted from the combined input of the Netherlands Commission for Environmental Assessment, any viewpoints submitted by other parties during the public consultation process following public announcement of the project, and external reviews by the Royal Haskoning engineering consultancy and International Safety Research Europe (Delta, 2009) (Rijksoverheid, 2010) (Glasson, et al., 2012).

2.2. Scope of the EIA

The EIA Guidelines document was used as the basis for preparing the EIA. It was adapted to fit this research by excluding and modifying sections considered less relevant and adding sections that were considered necessary for assessing MSR impacts, from studying the literature. The resulting outline of chapters taken from the EIA guidelines and additions constitute the scope of this EIA research. To enhance reliability any adaptations made were documented and can be found in appendix E.

The exact instructions in the EIA guidelines were followed as much as reasonably possible but the order of the environmental effects chapters was adapted: the "top 4" environmental effects associated with nuclear power that have historically met with most resistance were discussed first, and other environmental aspects follow in descending order of importance as judged by the author and supported by the literature. Included in the EIA's scope are:

Planned activity	**Chapter**
Technology description	**3.1.1**
Safety principles	**3.1.2**
Nuclear fuel cycle	**3.1.3**
Transport	**3.1.4**
Turbine & cooling	**3.1.5**
Construction	**3.1.6**
Decommissioning & dismantlement	**3.1.7**
Alternatives	**3.2**
Environmental effects	
Top 4	
Nuclear safety & radiation	**3.3.2**
Spent nuclear fuel and radioactive waste	**3.3.3**
Proliferation	**3.3.4**
Cost of electricity & other economic factors	**3.3.5**
Other environmental impacts	
Emissions into air	**3.3.6**
Soil and groundwater	**3.3.7**
Cooling water discharges	**3.3.8**
Noise	**3.3.9**
Nature	**3.3.10**
Landscape, cultural heritage, geology and archaeology	**3.3.11**
Wastewater discharges	**3.3.12**
Additional wind impacts	
Telecommunications & aviation	**3.3.13.1**
Shipping & navigation	**3.3.13.2**

Table 1: Scope of the EIA

2.3. Data collection

The finished template was then populated with EIA information on offshore wind power and conventional nuclear power from EIA reports for existing wind[6] and nuclear power[7] plant developments, and complemented with reliable information from sources such as official institutions and academic journals (Fig. 1).

For conventional nuclear power the preliminary EIA for the Borssele nuclear power plant was used because it closely matches the EIA guidelines. Where information was missing or incomplete, it was complemented with information from a Finnish EIA for the Hanhiviki nuclear power plant, which was selected for its quality and completeness and the fact that it describes the same reactor type.

As MSR EIA's do not exist, the information required to populate the MSR EIA had to be sourced primarily from academic journals and reports. These yielded sufficient reliable information to populate most of the MSR EIA[8], but some gaps and uncertainties still remained. These were carefully documented and turned into a series of questions, which were later discussed with three experts in the field. To enhance validity and reliability, an expert from each discipline relevant to this research was interviewed:

1. Dr. Jan-Leen Kloosterman, Associate Professor of **Nuclear Reactor Physics** with extensive knowledge of MSR physics and technology at Delft University of Technology in the Netherlands
2. Professor Rudy Konings, Head of Unit of Material Research with extensive knowledge of **MSR chemistry** at the Institute for Transuranium Elements (ITU) in Karlsruhe, Germany
3. Benjamin Soon, Executive Director of Flibe Energy, a prominent **company** developing MSR technology

For a full description of the expert interview process see appendix B, and the CD accompanying this report for the questions & answers.

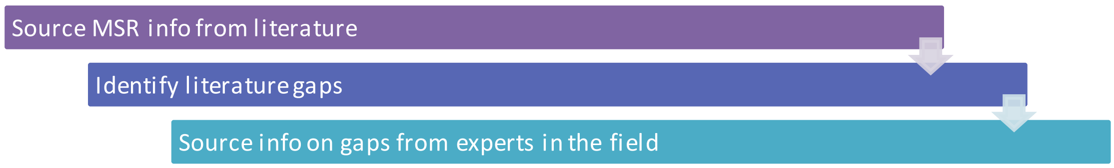


Figure 1: MSR data collection process

[6] Appendix D3
[7] Appendix D4
[8] Appendix D2

2.4. Impact evaluation

After collecting all of the data required for populating the EIA for each of the three technologies they were compared to each other. This was done in two ways: a simple **"Traffic Light Matrix"** recommended for presenting impacts to decision makers and investors that provides a quick overview of how the technologies' rank[9] relative to each other, and a more sophisticated "**Weighted Impact Matrix**" that assigns greater weight to impacts based on their perceived greater importance (Glasson, et al., 2012, pp. 132-136).

The Traffic Light Matrix has 4 tiers of performance: 1. Very good (green) 2. Good (yellow) 3. Mediocre (orange), and 4. Poor (red). In addition there is a "0" option if the item does not apply to a technology (light blue).

Assigning weights is very subjective and therefore susceptible to manipulation. If a slightly different approach to scoring is used, very different results can be attained. It is therefore important that this process is made transparent (Glasson, et al., 2012) by clarifying why weights were allocated as they were. For a full description of the weighting and ranking approach used see appendix C.

Weighting of issues was based on what are *perceived* to be the most important issues with nuclear power by relevant stakeholders, because regardless of how valid they are, they are real concerns and pose a potential barrier to pro-nuclear policy (Greenhalgh & Azapagic, 2009, p. 1060). Weights are usually assigned to environmental impacts based on the subjective judgement of an interdisciplinary team, based on the input of various stakeholders in the development (Canter, 1999, p. 9). Because an interdisciplinary team falls outside of the scope of this research, weights were assigned based on the author's subjective judgements. To lend greater reliability to the weighting process, assigned weights were made transparent and are supported by the literature.

In addition to the "top 4" impacts mentioned earlier, other environmental impacts were identified as carrying increased weight in an analysis by Greenhalgh & Azapagic (2009, p. 1060).These were the fuel cycle, nuclear transport, emissions into air, and pollution of soil and groundwater.

Wind energy has very different characteristics from nuclear power and a comparison is therefore not possible for each aspect. The aspects that did show similarity were compared and for negative impacts that do not apply to wind power, wind received a perfect score of 0. Additional categories were added for impacts that only applied to wind. See appendix D1 for a table depicting the wind/nuclear comparison framework.

[9] Ranking of LFTR's environmental impacts was always done conservatively so as not to understate any environmental impacts as recommended by the EIA guidelines (Rijksoverheid, 2010).

2.5. Limitations

Because the MSR is a technology that still has a long development trajectory before theory can be demonstrated in practice, some of the available information is based on extrapolation and “closest equivalent” assumptions (Soon, 2014). Practice can therefore still proof different than what is currently strongly suspected, but the information contained in this document represents the current state of the art.

Great effort was made to accumulate all information relevant to the MSR’s environmental impacts. If anything is still found lacking or incomplete, suggestions to improve this are welcomed as the aim is to provide a truly comprehensive overview of what may be expected.

The instructions that were used for this EIA are for a full-scale EIA, which typically takes 6-18 months (Glasson, et al., 2012, p. 85). The instructions therefor cannot be followed to the letter, in particular where certain simulations and methods are recommended that in themselves take considerable time, and require measurements or specialised software.

As mentioned previously, impact weights are usually assigned by an interdisciplinary team of expert stakeholders which fell outside of the scope of this research.

3. Environmental Impact Assessment

3.1. Planned activity

3.1.1. Technology description

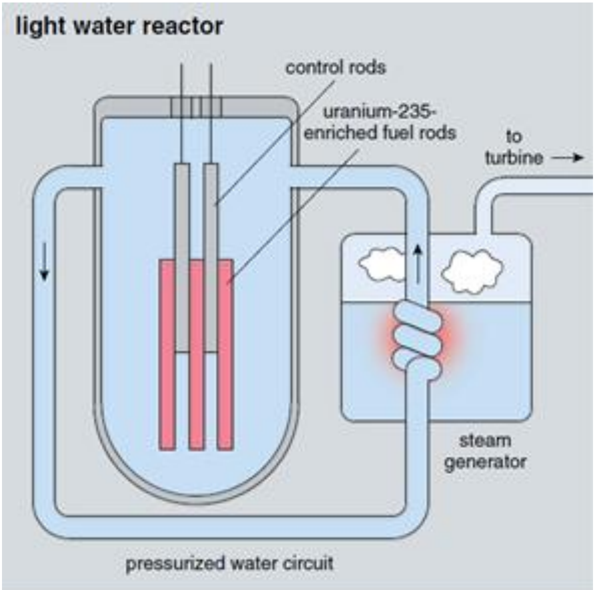


Figure 2: Pressurized Water Reactor (PWR) (R. Hargraves, 2010, p. 307)

3.1.1.1. The Light Water Reactor (LWR)

Like most nuclear reactors in operation today the reactor developments in the Dutch (Borssele) and Finnish (Hanhikivi) Environmental Impact Assessments used as examples in this report belong to the Light Water Reactor (LWR) class (Fig.2) (Delta, 2009) (Duke Energy, 2012) (Fennovoima, 2014).

LWR's can be subdivided further into two variants, the Pressurised Water Reactor (PWR) and the less common Boiling Water Reactor (BWR). The PWR keeps the water that absorbs heat from the core under high pressure to increase its boiling temperature and thus its capacity to take on heat without turning to steam, which it then transfers to a separate water loop via a heat exchanger that turns into steam and drives the turbine. The BWR allows the water that absorbs the core's heat to boil and generate steam to drive the turbine directly (Duke Energy, 2012) (European Nuclear Society, 2014). Both the Borssele and Hanhikivi nuclear power plants are PWRs (Delta, 2009) (Fennovoima, 2014).

The Pressurised Water Reactor (PWR)

In the PWR a core of solid uranium-235 fuel rods surrounded by pressurized water undergoes fission, generating large amounts of heat, as well as free neutrons that keep the nuclear chain-reaction going. The pressurised water has the dual function of cooling the core to prevent it from getting too hot, and transporting the heat that turns water in a separate loop to steam to drive the turbine. After the steam has passed through the turbine it is converted back into water by a condenser that is cooled by separate surface water loop (European Nuclear Society, 2014) (Delta, 2009) (Fennovoima, 2014). Table 2 shows the preliminary technical specifications for the Hanhikivi PWR.

Description	Value and unit
Reactor	Pressurized water reactor
Electric power	Approximately 1,200 MW (1,100–1,300 MW)
Thermal power	Approximately 3,200 MW
Efficiency	Approximately 37 %
Fuel	Uranium dioxide UO_2
Fuel consumption	20–30 t/a
Thermal power released in cooling to the water system	Approximately 2,000 MW
Annual energy production	Approximately 9 TWh
Cooling water consumption	Approximately 40–45 m^3/s

Table 2: Preliminary technical specifications for the Hanhikivi PWR (Fennovoima, 2014, p. 5)

The planned reactor developments in Borssele and Hanhikivi are both third generation reactors (Fig. 3). See appendix G1 for detailed information on these reactor types (Delta, 2009) (Fennovoima, 2014).

Figure 3: Impression of 3rd generation PWRs. Source: (Delta, 2009, p. 14)

3.1.1.2. The Molten Salt Reactor (MSR)

Molten Salt Reactors are fundamentally different from traditional nuclear reactor designs like the Light Water Reactor and belong to the generation IV nuclear power plant designs (Serp, et al., 2014).

While PWRs use solid uranium rods for fuel, MSRs use a mixture of liquid salts contained in pipes and tanks in which the fuel (uranium or thorium) is dissolved. This seemingly modest difference has significant implications for the way the reactor operates and its resulting characteristics.

Different types of MSRs exist[10]. Two general approaches are MSRs with a fast neutron spectrum, and MSRs with a thermal (or slow)[11] neutron spectrum[12]. Both approaches have their pros and cons and which is optimal is hard to say as international development efforts are not in agreement about this either. This should become clearer in the future as research progresses. What's more, what is considered "better" is subjective and very much dependent on what a particular party or nation deems to be the more desirable characteristics (Carpenter, 2003) (Konings, 2014) (Kloosterman, 2014). For more information about these two types see appendix G2.

These variants share many characteristics as well however which is why much of the research being done on either can apply to both. If the differences become relevant to any of the EIA items this will be mentioned but for the majority of the discussion it will not be.

A promising design is a thermal variant using thorium as a fuel. This variant is called the Liquid Fluoride Thorium Reactor (LFTR) or "Lifter" and will be assumed in the EIA unless specifically stated otherwise..

[10] Technically MSRs where the liquid salt is only used as a coolant can also be called MSR but these are not what is referred to in the context of this report.
[11] Slowed down by a material (e.g. graphite) called the "moderator" (Carpenter, 2003).
[12] Within these, different configurations exist as well (Kloosterman, 2014), but these shall be left out of the current discussion.

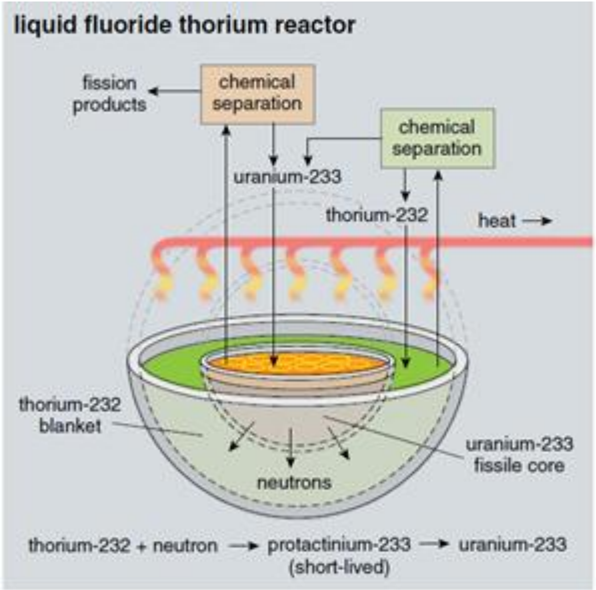


Figure 4: Liquid Fluoride Thorium Reactor (LFTR) (R. Hargraves, 2010, p. 307)

The Liquid Fluoride Thorium Reactor (LFTR)

In the LFTR design a core of molten salts and dissolved uranium is surrounded by a separate "blanket" of molten salts containing thorium (Fig.4).

The uranium in the core serves two purposes. One is to generate heat to drive electricity production and the other is to change the thorium in the blanket into additional uranium fuel through transmutation. This is achieved when the uranium fissions and releases neutrons that are absorbed by the thorium atoms, causing it to decay into the same uranium-233 that is in the core. This additional fuel is then removed from the blanket through chemical separation and transported to the core where it repeats the processes of generating heat and turning more thorium into uranium.

The liquid state of the fuel makes it far simpler to manipulate than the solid fuel of the PWR, which traps fission products inside its structure. This allows easy removal of fission products that have a negative effect on the reactor or the nuclear chain reaction, or of those that have commercial (e.g. medical) applications (Hargraves & Moir, 2010) (LeBlanc, 2009) (Hart, 2011).

Another LFTR benefit is automatic load following: if more power is required more heat it drawn from the molten salt. This reduces the temperature of the salt, which increases reactivity and heat production (Hargraves & Moir, 2010) (Weinberg Foundation, 2013).

Flibe

The LFTR's liquid fuel can have different configurations of ingredients depending on the desired properties. A mixture of lithium-fluoride and beryllium-fluoride is usually considered and is commonly referred to as "Flibe" ($LiF\text{-}BeF_2$). Flibe has a boiling point of 1430 ^{0}C, allowing it to take on tremendous amounts of heat without risking it turning to steam (D. T. Ingersoll, sd) (Sohal, 2010). In addition to serving as a coolant and transporting heat, it acts as a moderator which means it slows down fast neutrons to increase the chances of fission occurring and sustains the nuclear chain reaction (Sorenson, 2012) (Carpenter, 2003).

This does mean that the LFTR needs an installation to cleanse and maintain the FLiBe mixture, which runs parallel to the reactor component (Kloosterman, 2014).

Chemical component

Fission products are separated out of the fuel salt in the processing installation by using fluorination and plating techniques. Fuel salt processing demands will be higher in thermal spectrum MSRs like the LFTR than in fast spectrum MSRs (Hargraves & Moir, 2010) (Konings, 2014) (Kloosterman, 2014).

3.1.1.3. Wind

Offshore wind power is commonly regarded as a sustainable source of energy that has the potential to be deployed on a large scale, will become increasingly economically competitive, and will represent the bulk of future European wind power investments (Fig. 5) (Carbon Trust, 2008) (EWEA, 2009) (Kost, et al., 2013) (UCS, 2014) (USEIA, 2014).

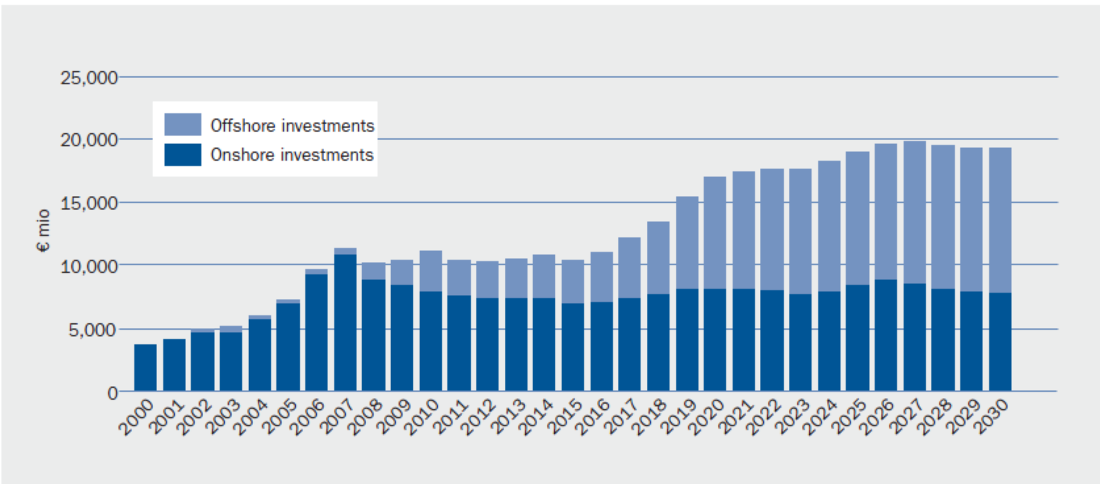


Figure 5: Wind energy investments 2010-2013 (€ mio). Source: (EWEA, 2009)

Wind turbines come as horizontal axis versions (HAWTs) and vertical axis versions (VAWT) with HAWTs being the most common type. Their number of blades can range from just one to many, but the three bladed design is most common.

Turbines used by utilities usually range from 250 kW to about 5 MW. The largest turbines can even go beyond that, as is the case with the massive 135 meter high 7.58 MW Enercon-126 turbine. Turbines used for utility scale electricity production are usually placed in groups called "wind farms" to take advantage of favourable wind sites.

A wind turbine consists of three main parts, the tower, the blades and the box behind the blades holding the machinery that turns the motion of the blades into energy, called the "nacelle" (Fig. 6). The nacelle typically contains an axle running from the blades into a gearbox where the speed of rotation is greatly increased to produce AC electricity. To ensure electricity is produced at the right speed and voltage, the blade rotation speed is kept constant either by adjusting the orientation of the blades according to the wind speed, or by allowing the blades to rotate at different speeds while sophisticated power controls inside the nacelle provide the necessary adjustments (Boyle, 2012) (UCS, 2013).

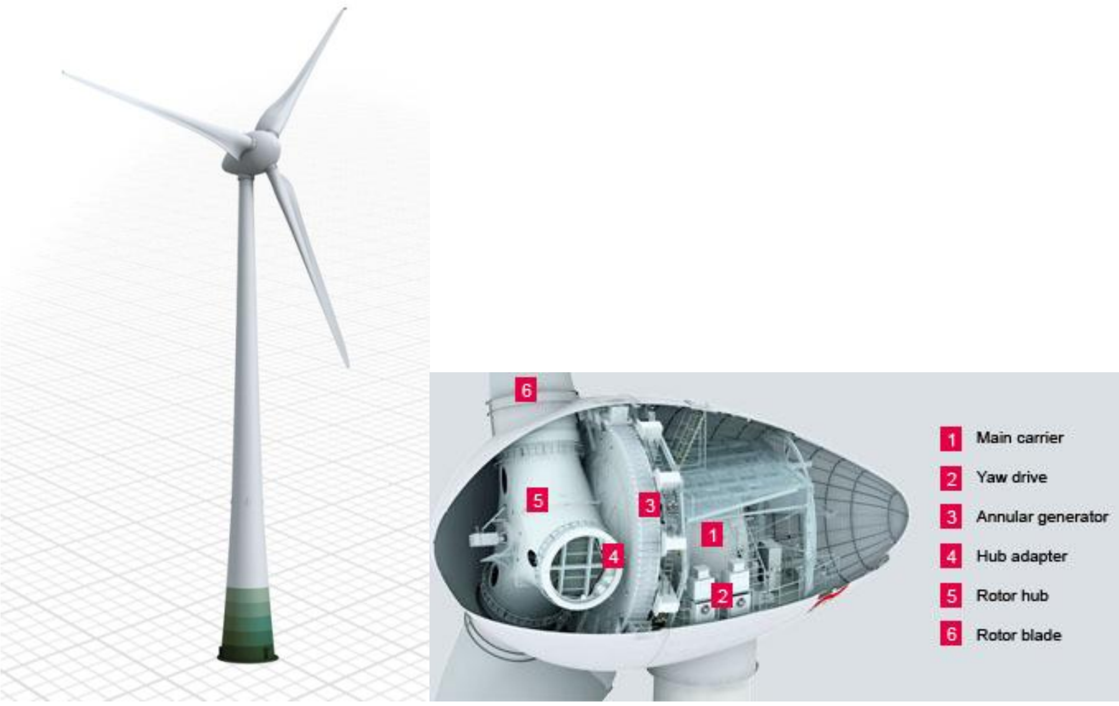


Figure 6: Enercon-126. Source: (Enercon, 2014)

3.1.2. Safety principles

3.1.2.1. The Pressurized Water Reactor

The main dangers in PWRs are steam explosion and meltdown.

Meltdown occurs when the solid uranium fuel rods in the reactor core cannot be adequately cooled anymore, causing the surrounding water to boil off. The uranium's temperature then increases to such an extent that the fuel rods melt and if this molten uranium escapes the containment structure this can result in severe radioactive contamination of the environment (Matson, 2011) (UCS, 2011) (European Nuclear Society, 2014).

The other major danger in PWRs is pressure explosion. The cooling water in these reactors is kept under high pressure to increase its boiling temperature and thus its capacity to take on heat energy without turning to steam. If the water's containment is breached, pressure is lost and the water instantly returns to its natural lower boiling temperature. Because the water still has a temperature far above 100 ^{0}C it boils and flashes to steam instantly, causing it to suddenly expand which creates an explosive reaction (LeBlanc, 2009) (Hargraves & Moir, 2010) (Krepel, et al., 2014).
In the PWR the radioactive substances are shielded from the environment by the "multi barrier approach":

1	The nuclear fuel itself, which traps radioactive materials in its solid structure
2	The sheathing/cladding tubes around the fuel rods
3	The cooling water and reactor vessel surrounding the fuel rods and keeping its temperature at safe levels
4	A "core catcher" in some cases, a device to accommodate the molten core material in case of a meltdown
5	A large steel safety shell and concrete dome around the reactor to protect against steam explosion and to prevent any radioactive substances escaping in case of an accident

Table 3: PWR safety measures. Source: (Krepel, et al., 2014, p. 383)

If any of these barriers is threatened or compromised, active and passive safety systems come into effect to either shut the reactor down, provide cooling of the reactor (core), or prevent radioactive substances from spreading (Delta, 2009) (Krepel, et al., 2014) (World Nuclear Association, 2014).

3.1.2.2. The Liquid Fluoride Thorium Reactor

The LFTR's liquid fuel gives it very different properties from the solid fuelled PWR that result in an inherently safe design. The danger of meltdown is not an issue because the fuel is supposed to be in a molten state and the facility is designed to safely accommodate this. The other main danger in PWRs, the risk of a pressure explosion, is not relevant either because the coolant salt does not have to be kept under pressure for it can reach temperatures of up to 1400 ^{0}C without boiling (LeBlanc, 2009) (Hargraves & Moir, 2010) (Kamei & Hakami, 2011) (Weinberg Foundation, 2013) (Serp, et al., 2014).

If the coolant salt were to escape its containment, it would simply spill out into catch basins and flow into drain tanks where it would passively cool and harden into a solid at about 500 ^{0}C, trapping dangerous fission products inside. If fuel salt were to somehow spill outside of the reactor it would similarly cool and harden into an inert mass, only posing a danger to its immediate surroundings, and several weeks of clean up would be required (Hargraves & Moir, 2010) (LeBlanc, 2009) (Weinberg Foundation, 2013) (Krepel, et al., 2014). (Konings, 2014) (Soon, 2014) (Kloosterman, 2014).

To protect against unwanted temperature increases or other incidents the LFTR relies on passive safety systems which will be detailed in chapter 4.2 to avoid duplication.

3.1.3. Nuclear fuel cycle Weight: 4

An important aspect of (nuclear) energy generation is the "Nuclear fuel cycle", or all the processes involved in producing fuel, processing spent fuel, and its storage (Fig.5). Although mostly performed by companies higher up and lower down the nuclear supply chain that are often located in different countries, these activities are considered to be inextricably linked to nuclear power production (Delta, 2009).

3.1.3..1. The Pressurized Water Reactor

PWR's run on uranium which has to be mined, milled, converted, enriched, fabricated into fuel elements, and transported as part of the "front-end" or "upstream" fuel related activities, and spent fuel has to be conditioned, potentially reprocessed, put in interim storage and finally placed in permanent long-term storage as part of the "back-end" or "downstream" of the fuel cycle (Weisser, 2006) (Fthenakis & Kim, 2007) (Sovacool, 2008) (Lenzen, 2008) (Beerten, et al., 2009). For a detailed explanation of the uranium fuel cycle processes see appendix G3.

The nuclear fuel cycle can be classified as "open", or as "closed". In the conventional open nuclear fuel cycle spent nuclear fuel is disposed of and put into storage after it is removed from the reactor. In the closed nuclear fuel cycle spent fuel is treated in a reprocessing facility to recycle part of the spent fuel. Disadvantage of reprocessing are that it is costly and presents proliferation and safety hazards (Sovacool, 2008).

Either following processing or immediately after being removed from the core the spent fuel is moved to onsite water pools to cool down for 3-10 years after which it is placed in special dry storage containers for interim storage for a further 30 years. Finally it is repackaged and disposed of in a permanent facility for long term storage (Delta, 2009) (Fennovoima, 2014). For additional information see the "Spent nuclear fuel and radioactive waste" section of this report.

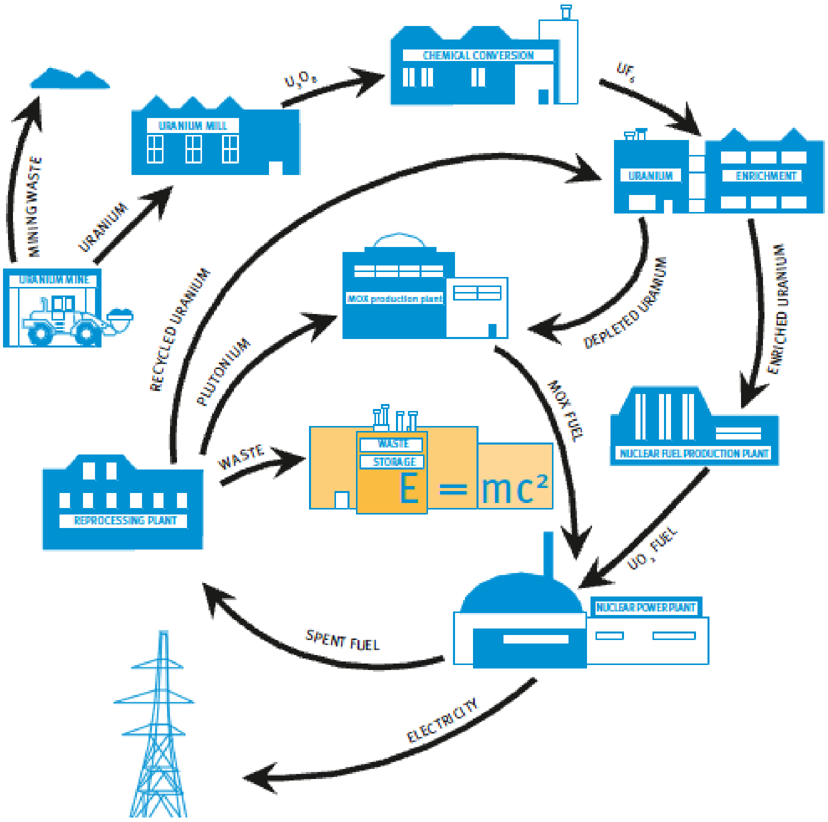


Figure7: The closed nuclear fuel cycle. Source: (Delta, 2009, p. 19)

3.1.3.2. The Liquid Fluoride Thorium Reactor

Thorium

Instead of uranium, the LFTR runs on thorium fuel that is transmuted into uranium. 3-4 times more thorium than uranium is estimated to exist[13][14] worldwide and it is much easier to extract (LeBlanc, 2009) (Juhasz, et al., 2009) (Hargraves & Moir, 2010) (World Nuclear Association, 2012). (Kloosterman, 2014).

Because of the much higher energy yield from thorium compared to an equal amount of uranium these reserves are enough to power the entire world for tens of thousands of years, as opposed to 100-230 years for uranium, under present day technological and market conditions (Juhasz, et al., 2009) (Fetter, 2009) (Foro Nuclear, 2011) (National Nuclear Laboratory, 2012) (Kloosterman, 2014).

Mining

Thorium is currently mined as an unwanted by-product of rare-earth mining in such quantities that it seems unnecessary to purposefully mine for thorium (Hargraves & Moir,

[13] Excluding the uranium in the oceans (WISE, 2014)
[14] About 6.2 million tonnes (World Nuclear Association, 2014)

2010) (Soon, 2014) (Konings, 2014). Like most forms of mining, rare-earth mining comes with environmental consequences such as the release of "radionuclides, dust and metal, and rare earth elements" (MIT, 2014).

Milling, conversion & enrichment

Natural uranium requires highly energy intensive enrichment because only very little of the uranium coming out of the ground is the isotope required for use as nuclear fuel, Uranium-235. Natural thorium on the other hand consists almost entirely of the isotope used as nuclear fuel, thorium-232. There is therefore no need for any enrichment of thorium or associated processes. However, thorium is not fissile like uranium but fertile, meaning it needs a fissile material to kick-start the nuclear chain reaction for which it needs to rely on uranium isotopes. Theoretically this would only have to happen at start-up, after which the reactor produces its own uranium (Weisser, 2006) (Watson, 2013) (Konings, 2014).

Fuel fabrication

There still is a need to fabricate fuel but in a different way. Whereas in PWRs ceramic uranium pallets are stacked to form solid fuel rods, the LFTR needs liquid fuel which has to be fabricated.

The fabrication of Thorium Tetra-fluoride to be added to the blanket salt of a LFTR could be conducted on-site or centrally depending on the adopted local fuel supply chain or regulatory requirements (Soon, 2014).

Fuel processing

In a LFTR rather than after coming out of the reactor as waste, the liquid fuel is constantly processed to remove fission products (Weinberg Foundation, 2013) (Konings, 2014).

Fuel transport

LFTR fuel or its components will likely need to be transported in some form. This is not expected to go beyond what is already commonly done in transport of chemicals or radioactive substances (Konings, 2014). (See chapter 3.1.4.)

Waste storage

LFTR waste will be far smaller in quantity and require storage for a shorter period of 300 years, but will be stored in geological repositories like PWR waste (Hargraves & Moir, 2010) (Soon, 2014) (Konings, 2014). (See chapter 4.3)

3.1.3.3. Comparison

The thorium fuel cycle is significantly simplified compared to uranium as enrichment is not required and waste related requirements are greatly reduced. The fuel cycle does not apply to wind power.

Thorium will still need to be produced but the effects of mining are already incurred through the pursuit of rare earths and driven by products such as smart phones, camera lenses, and magnets, such as the magnets used in many wind turbine designs (Hilsum, 2009) (Biello, 2013) (Kaiman, 2014). Some uranium will still be required to kick start the nuclear chain reaction however.

Based on these considerations the following ranking was assigned to the environmental impacts of the three technologies' fuel chain.

The Pressurized Water Reactor	**4**
The Liquid Fluoride Thorium Reactor	**2**
Wind	**0**

3.1.4. Transport Weight: 2

3.1.4.1. The Pressurized Water Reactor

Facilities involved in the nuclear fuel cycle such as mines, enrichment plants, power plants, waste reprocessing facilities, and nuclear waste storage are located all around the world and radioactive materials need to be transported between them.

Roughly 20 million shipments of radioactive materials are transported each year in trucks, trains, and by ship, around 1000 of which are related to the nuclear fuel cycle. 80.000 tons of high level waste in 20.000 separate consignments has been transported over millions of kilometres since 1971. Although there have been accidents, a package containing highly radioactive material has never been breached.

These transports fall under the strict regulations of the International Atomic Energy Agency (IAEA) which requires stringent packaging standards that depend on the potential hazard of the nuclear material (World Nuclear Association, 2014):

Designation	Material	Packaging method
Low risk material	Uranium oxide, low-level waste	Drums inside industrial containers
Medium level	Medical isotopes	"Type A" packaging designed to withstand minor accidents
High level	High level waste	"Type B" packaging (Fig.8) highly secure casks designed to fully enclose their cargo and withstand any potential accident

Table 4: Nuclear transport methods. Source: (World Nuclear Association, 2014)

Figure 8: Type B packaging. Source: (World Nuclear Association, 2014)

3.1.4.2. The Liquid Fluoride Thorium Reactor

Fuel transport could be a part of LFTR energy generation. If Flibe fuel is prepared at a central location instead of at the reactor site to cut costs, this will involve shipping to the reactor. The transport of Flibe would be chemical transport which requires safety measures but nothing unfamiliar. If fuel transport would include radioactive materials this would require similar precautions as are currently taken for radioactive materials such as uranium dioxide, uranium hexafluoride, or plutonium oxide (Konings, 2014) (Soon, 2014).

In addition to that, some of the fission products with commercial value such as medical isotopes that have been separated out of the fuel salt will have to be transported.

These will require similar packaging as isotopes from current reactors (Kloosterman, 2014). The core could also potentially need periodic shipping for maintenance, but this depends entirely on the chosen approach (Soon, 2014). The LFTR will produce much less nuclear waste and therefore requires less nuclear waste transport (Hargraves & Moir, 2010).

3.1.4.3. Wind

Wind turbines do not require fuel to be transported. The most significant transport required is related to construction and decommissioning activities such as the laying of cable and building a substation on land the transport of heavy (turbine) components. If manufacturing takes place far away from where turbines are to be deployed, this could necessitate transport over large distances (Acher, 2010) (RWE, 2011).

3.1.4.4. Comparison

The LFTR is expected to have advantages over the PWR due to the simplified fuel chain, but transport seems least demanding for wind power, as it only shares construction and decommissioning transport requirements but no nuclear fuel cycle transport whatsoever. The following ranking was assigned:

The Pressurized Water Reactor	**3**
The Liquid Fluoride Thorium Reactor	**2**
Wind	**1**

3.1.5. Turbine & cooling

3.1.5.1. The Pressurized Water Reactor

Pressurized Water Reactors (PWR) use large amounts of cooling water to cool the steam that drives the turbines (Fig. 9) back to liquid form, so that it may be recycled to take on new heat from the reactor core. This cooling water is usually sourced from nearby large bodies of water (Delta, 2009) (Rijksoverheid, 2010).

Cooling water intake depends on how much energy is produced. A 1200 MW plant will need around 40-45 m^3/seawater/sec for cooling. Cooling water is filtered for impurities and objects before being led to the condenser after which it is discharged in a sea or lake having increased about 10-12 ^{0}C in the process (Fennovoima, 2014).

Taking in large amounts of water can have effects on aquatic ecology by sucking them in. In addition to that the temperature differences caused by discharging warm cooling water can affect marine ecology as well and reduce the water's suitability as cooling water for other power plants in the area. In combination with other power plants the cumulative effects of multiple cooling water streams can have an exacerbated effect.

An alternative method of cooling are cooling towers which are sometimes part of PWRs but were not planned for the Borssele and Hanhikivi nuclear power plants as direct cooling with (sea)water provides a few percentage points higher efficiency (Delta, 2009) (Rijksoverheid, 2010) (Fennovoima, 2014) (World Nuclear Association, 2014).

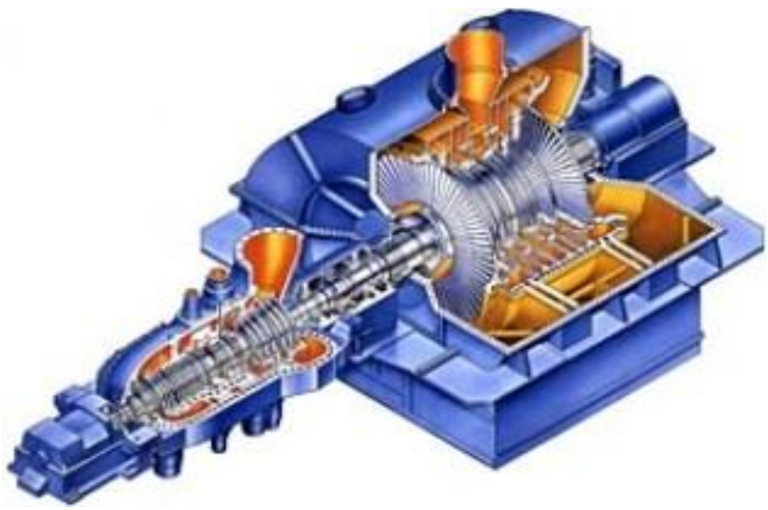


Figure 9: Steam turbine. Source: (World Nuclear News, 2007)

3.1.5.2. The Liquid Fluoride Thorium Reactor

Instead of the traditional Rankine cycle steam turbine that PWRs use, the LFTR's high operating temperatures make it ideally suited to the Brayton cycle gas turbine (Fig. 10,9) (LeBlanc, 2009) (Weinberg Foundation, 2013) (Krepel, et al., 2014).

Brayton cycle turbines use a gas (e.g. nitrogen, helium, CO_2 or compressed air) instead of steam to drive electricity production. In the LFTR the liquid fuel salt would heat the gas causing it to expand through the turbine and produce electricity. The gas is then cooled back to its starting temperature again after which the cycle repeats itself (Sabharwall, et al., 2011) (Weinberg Foundation, 2013).

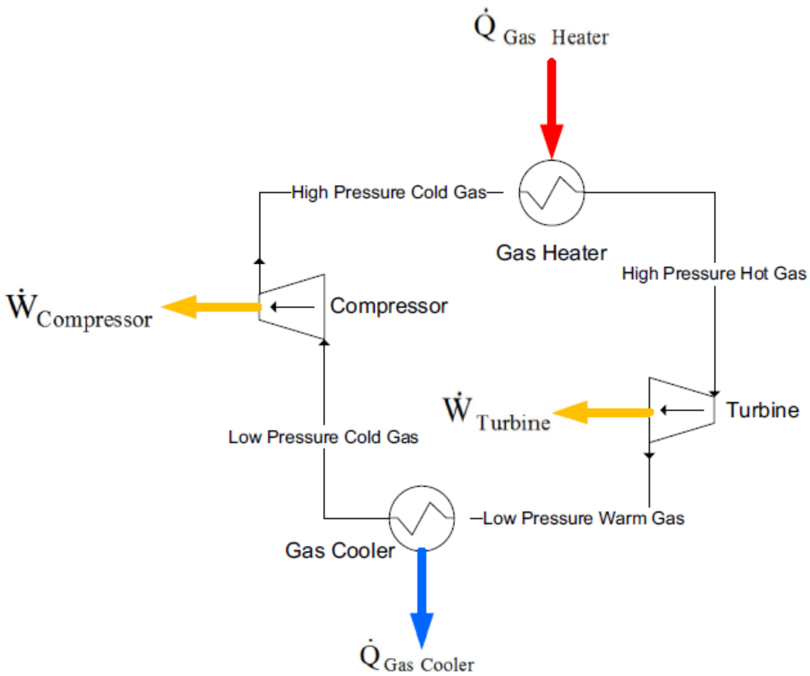


Figure 10: Simple Brayton cycle diagram. Source: (Sabharwall, et al., 2011, p. 12)

Only small scale Brayton cycle turbines are currently in use but the process is being scaled up to be coupled with the Fluoride High Temperature Reactor (FHR). This is another high temperature reactor currently under development in the Unites States, which is expected to be ready well before the MSR[15] (Weinberg Foundation, 2013).

Using the Brayton cycle has several important advantages for the LFTR. Its high temperature operation prevents the fuel salt from freezing, it enables efficiencies of 45-

[15] There is no reason to believe that this development will not succeed, but if need be the LFTR can also be coupled with a supercritical steam turbine (Soon, 2014).

50% and it provides a demonstrated solution to the tritium production issue[16] (LeBlanc, 2009) (Juhasz, et al., 2009) (Hargraves & Moir, 2010) (Weinberg Foundation, 2013).

Another advantage is that if needed the Brayton cycle can even do without water cooling and be entirely air cooled, which allows LFTRs to be built away from large bodies of water (LeBlanc, 2009) (Weinberg Foundation, 2013) (Morrow, 2014) (Soon, 2014). Water cooling would be the more efficient option however so this will be the favoured method whenever possible (Soon, 2014).

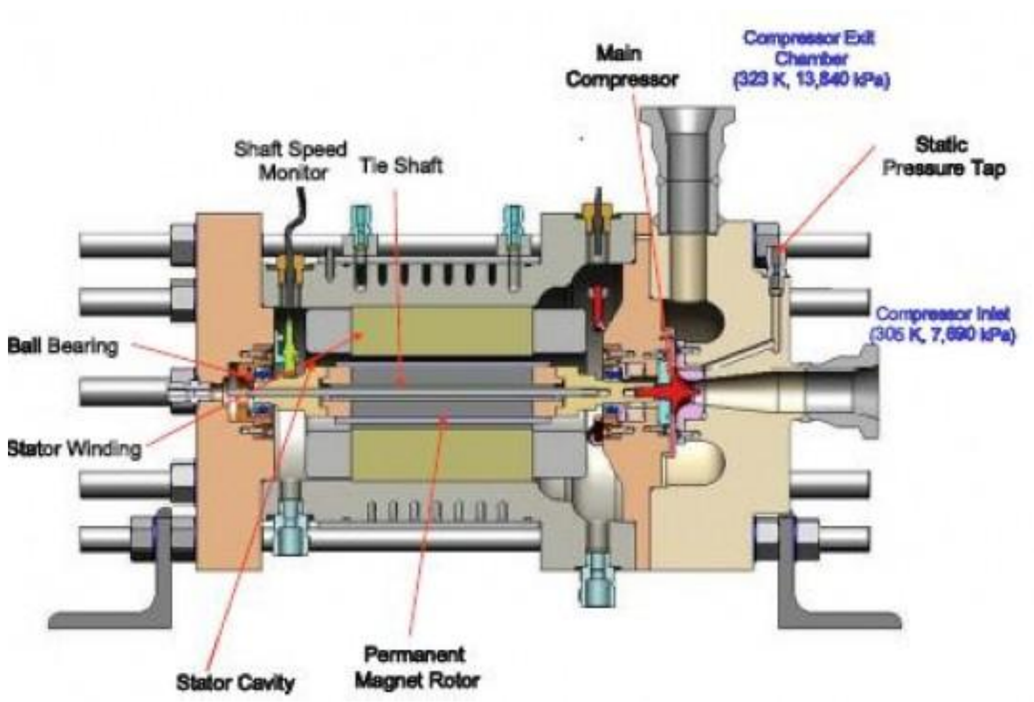


Figure 11: Closed loop Brayton cycle from Sandia National Laboratories. Source: (Morrow, 2014)

[16] See chapter 3.3.2.1

3.1.6. Construction work — Weight: 1

3.1.6.1. The Pressurized Water Reactor

Constructing a nuclear power plant is a large and complicated project. Although hundreds of plants have been constructed over the years, projects still run into dramatic schedule and cost overruns. A major current reason for this is that there is heavy worldwide competition for the resources, commodities, and engineering capability needed to construct new power plants. Notable is the fact that worldwide only two companies[17] have the heavy forging capacity to make the largest steel components used in nuclear power plant construction (Schlissel & Biewald, 2008) (Thurner, et al., 2014) (World Nuclear Association, 2014).

The entire process of building a nuclear power plant should take an estimated 9 years including licensing procedures, with actual construction and site preparation taking 4 and 1.5 years respectively (Nuclear Energy Institute, 2014).

Site preparation can include things like felling trees and rock excavation as well as the development of roads and other infrastructure. The buildings associated with the actual power plant as well as cooling water inlet and discharge structures have to be built, requiring as much as 3500 people working at the plant construction site during the busiest period in the Hanhikivi plant example (Fennovoima, 2014).

3.1.6.2. The Liquid Fluoride Thorium Reactor

It is not yet possible to say precisely what LFTR construction will entail but there indications as to what can be expected.

On the one hand LFTR construction time is likely to be shortened because most of the system is modular, and potentially much less on-site preparation is required (Soon, 2014). On the other hand the chemical processing plant needs to be constructed as well which will add time (Konings, 2014). Earlier models may take longer to complete than later versions (Kloosterman, 2014), as construction experience increases.

Other factors potentially contributing to easier construction are the superfluity of a coolant injection system, and the large concrete dome that is built as part of PWRs to contain any gases, steam, or explosions (Hargraves & Moir, 2010).

[17] The French Creusot Forge and Japan Steel Works

3.1.6.3. Wind

Offshore construction is more complicated than onshore and involves building foundations by hammering in long cylindrical steel tubes into the seabed underwater, bolting the prefabricated turbine to the foundation, and attaching the nacelle and blades to the turbine.

In addition to the turbines, offshore substations are also required and array cables have to be laid. The London Array required over 400 km of cable between the turbines the substations, and export cables between the substations and the shore. The onshore component then requires additional substations and cabling to connect the array to the grid (London Array, 2014) (London Array, 2014).

While onshore construction can take as little as a few weeks, large offshore wind farm projects take longer, with the London Array taking about 4 years from initial preparatory work to finalising construction, with actual construction taking 1-2 years. At the peak of construction, as much as a thousand people worked on the project at the same time (London Array, 2014) (EWEA, 2005).

3.1.6.4. Comparison

Nuclear power plant construction is a huge undertaking and projects have run into considerable budget and schedule overruns in the past. There are arguments suggesting that LFTR construction will take a shorter amount of time than the PWR, but some additional construction will be required as well. Like the PWR, the LFTR will probably require specialised engineering and components so the current scarcity of these could present problems. If not insurmountable, they may still be significant by having a negative effect on total costs. Constructing offshore wind turbines is not as complex as building a nuclear power plant but is still a feat of engineering that takes several years. The following ranking was assigned:

The Pressurized Water Reactor	**4**
The Liquid Fluoride Thorium Reactor	**3**
Wind	**1**

3.1.7. Decommissioning and dismantlement Weight: 1

3.1.7.1. The Pressurized Water Reactor

At the end of its operational lifetime, a nuclear power plant still has an important phase to go through that could potentially have significant environmental implications. The decommissioning of nuclear installations is a point of contention that according to some is a highly hazardous and expensive undertaking while others believe it can be safely done (Greenpeace, 2010) (World Nuclear Association, 2014).

The majority of the plant does not become radioactive or only very slightly, and can be easily removed and recycled. The remainder poses radiation risks and has to be handled with care.

Several options for decommissioning exist:

Immediate Dismantlement	The installation is completely dismantled and the site ready for re-use in a matter of years
Safe Enclosure or "Safstor"	The facility's radioactive materials are allowed to decay to safer levels inside the reactor for 40-60 years
"Entombment"[18]	Site is essentially designated as a waste storage site by reducing the radioactive area and then encapsulating it in a safe containment, usually concrete

Table 5: Decommissioning methods. Source: (World Nuclear Association, 2014)

For detailed explanation of the immediate dismantlement process relevant to the Borssele reactor see appendix G4.

3.1.7.2. The Liquid Fluoride Thorium Reactor

Decommissioning will potentially be much simpler for LFTRs than for PWRs because of the modular nature of LFTR plants. The cores can be de-fuelled and shipped back to a specialised facility for disassembly and recycling. This is a significant advantage over existing technology that needs to be disassembled on site and decontaminated. A LFTR site could be recycled, or repurposed relatively easily following site decontamination (Soon, 2014). The entire primary circuit as well as the chemical part of the plant also needs to be decommissioned however, which adds to the amount of contaminated components that have to be dealt with (Konings, 2014) (Kloosterman, 2014).

[18] This option is reserved for exceptional circumstances like a severe accident however and not recommended by the International Atomic Energy Agency (IAEA) (Knaack, 2012).

3.1.7.3. Wind

The impacts of decommissioning of offshore wind turbines should be lesser or equal to construction (RWE, 2011) and much easier than nuclear power plant decommissioning as there is no radioactive component to deal with (Gipe, 2013). Parts of the turbine can be recycled and if turbines are still in good condition they can be reconditioned and sold second-hand to buyers in Eastern-Europe, South America and Asia (BBC, 2013).

3.1.7.4. Comparison

The decommissioning of nuclear power plants is a relatively complicated undertaking due to the radioactive components that have to be dealt with. The process could be easier for LFTRs due to their modular design, but the larger area that has come into contact with radioactive materials provides an additional burden. Decommissioning is much easier for wind turbines than nuclear power plants and is not easily comparable due to the absence of any radioactive materials. The following ranking was assigned:

The Pressurized Water Reactor	**4**
The Liquid Fluoride Thorium Reactor	**3**
Wind	**1**

3.2. Alternatives

3.2.1. Location alternatives

The choice of location determines the environment that is affected.

Many options for siting a PWR exist but some criteria have to be met. A large body of water is usually required for sourcing cooling water, and in most cases a location away from urban areas will be easiest as residents may not welcome a nuclear power plant “in their backyard” (Parkins & Haluza-DeLay, 2011, p. 26).

The LFTR has more flexibility in siting as the Brayton cycle gas turbine makes locations away from bodies of water theoretically possible (Weinberg Foundation, 2013). LFTRs can be scaled, which further increases siting flexibility (Sorenson, 2011). Finally, LFTR’s superior safety features potentially make it more suitable for siting close to populated areas (LeBlanc, 2009) (Hargraves & Moir, 2010) (Kamei & Hakami, 2011) (Weinberg Foundation, 2013) (Serp, et al., 2014).

Wind turbines are restricted by requiring sites with adequate wind speeds that can accommodate wind farms’ large surface areas (Carbon Trust, 2008) (AWEA, 2013).

3.2.2. Design alternatives

A wide range of different nuclear power plant designs exist but the PWR is most common (Duke Energy, 2012) (European Nuclear Society, 2014). For a description of 3rd generation reactor design alternatives see appendix G1.

MSRs can also come in many different forms. Alternative sizes, cooling method, choice of moderator, fuel salt configuration, nuclear fuel, start-up fuel, construction materials, construction method (on-site, centrally, modular), building design, and reactor & chemical component layouts are all possible, each with slightly different characteristics (Sohal, 2010) (E. Merle-Lucotte, 2012) (Krepel, et al., 2014) (Heuer, et al., 2014) (Kloosterman, 2014).

Wind turbines come in many different forms as well. Different sizes, blade configurations (vertical or horizontal), number of blades, onshore and offshore are possible to name a few. It is also possible to produce turbines without using the rare earth neodymium thus mitigating the environmental impact of rare earth mining, as Enercon have done (Enercon, 2011).

3.3. Environmental effects

3.3.1. General

This section details the relevant environmental effects that can be expected from PWR, LFTR, and offshore wind power development. The EIA guidelines describe general requirements for presenting information on environmental effects which have been followed wherever possible. See appendix F for this list.

3.3.2. Nuclear safety and radiation Weight: 5

3.3.2.1 Normal operation, events and accidents

The EIA guidelines require the description of the effects on safety during *normal operation, "events" (malfunctions), design accidents, and severe or beyond-design accidents* and the principles applied to assure safety during all of these. See appendix H1 for additional information on this chapter.

Normal operation - PWR

Pressurized Water Reactors are designed to not pose any significant danger to the environment during normal operation. Any radiation coming from the plant's buildings or ventilation shaft that can come into contact with local residents and passers-by is much lower than naturally occurring radiation levels. Even so, all radiation is carefully monitored (Delta, 2009) (Rijksoverheid, 2010).

Normal operation - LFTR

LFTR's fuel salt is continuously processed in a reprocessing plant to remove dangerous fission products by using plating and fluorination techniques (Hargraves & Moir, 2010). This creates a higher radiation risk during operation but prevents these products from releasing all at once in case of a severe accident (Weinberg Foundation, 2013). Such a release occurred during the Fukushima Daiichi disaster, where they formed the major contributor to radioactive material release (Krepel, et al., 2014). The increased radiation during operation is safely limited to a contained area within the reactor called the "hot zone" however, resulting in a very low danger to the population and the environment (Soon, 2014).

Fuel salt can contain hazardous substances such as beryllium but these are familiar chemistry that is routinely used in other industries (Hargraves & Moir, 2010) (Halper, 2013) (Serp, et al., 2014) (Konings, 2014) (Soon, 2014) (Kloosterman, 2014) (World Nuclear Association, 2014) (Konings, 2014).

The LFTR is expected to produce more of the potentially hazardous hydrogen isotope tritium than the PWR, but less than heavy water reactors (Rho & Lee, 1998) (Filho, et al., 2013). This problem could be mitigated by keeping the tritium completely within the containment boundary. This is achieved by chemically trapping the tritium in the secondary loop before it leaves the containment boundary and the use of a closed cycle gas turbine ensures that even what little that somehow diffuses to the Power Conversion System (PCS) is trapped and removed (Weinberg Foundation, 2013) (Soon, 2014).

Events (malfunctions) - PWR

In case of events such as the primary or secondary cooling system failing, the PWR is equipped with back-up systems that activate automatically and restore normal conditions, by cooling in this case. Events can occur several times during the nuclear plant's lifetime and do not result in radioactive discharges beyond licensed limits (Delta, 2009) (Rijksoverheid, 2010).

Events - LFTR

LFTRs come with a powerful safety feature that is entirely passive[19]. If for any reason the temperature of the liquid fuel were to increase, this causes the liquid to expand. The same amount of fissile material will now be spread over a larger area, reducing the effective area for neutron absorption and potential for fission reactions. The decrease in reactions will then automatically lower the fuel's temperature back to safe levels (LeBlanc, 2009) (Juhasz, et al., 2009) (Hargraves & Moir, 2010) (Weinberg Foundation, 2013) (Schaffer, 2013) (Serp, et al., 2014) (Krepel, et al., 2014).

Design accidents - PWR

"Design accidents" are accidents that are expected to occur on rare occasions and unlike events are not entirely without consequences. Provisions are made in the PWR in the form of safety systems that can safely handle their occurrence. The effects of design accidents should be limited in that the power plant can be brought back online following the accident, potentially after repairs. Design accidents can result in the emission and discharge of radioactive substances and precautions have to be taken to limit their effect on the environment and population. The potential effect on the surrounding area depends on the specific location and reactor characteristics (Delta, 2009) (Rijksoverheid, 2010).

[19] No human or machinery intervention is needed for it to work

Design accidents - LFTR

In case of the LFTR's equivalent of a "design accident" the liquid fuel can simply be drained into safe containment basins that are specially designed to control any of the fuel's potential hazards. What's more, the LFTR will come with a plug of frozen fuel salt at the lowest point of the piping system that is kept frozen by electric fans. If the fuel salt's temperature rises too high or power to the reactor (and the fans) is completely lost, the plug will automatically melt and the liquid will drain into the containment basins. The important difference with other reactor types is that instead of power and human intervention being required to safely shut a reactor down, power is required to *prevent* the reactor from shutting down. Therefore, if control over the reactor is lost in case of emergency it will always safely shut itself down (LeBlanc, 2009) (Juhasz, et al., 2009) (Hargraves & Moir, 2010) (Weinberg Foundation, 2013) (Schaffer, 2013) (Serp, et al., 2014) (Krepel, et al., 2014).

The facility includes storage facilities for Fluorine and Hydrogen which are used in the processing procedure. These are non-radiological facilities and accidents here are considered 'normal industrial' since Fluorine is toxic and Hydrogen is explosive. They do not pose a threat to the reactor itself however (Soon, 2014).

Beyond design accidents - PWR

"Beyond-design accidents" are highly unlikely but very severe accidents that go beyond the control of the reactor's active safety systems. In such events the reactor cannot be adequately cooled anymore which can lead to dangerous temperature increases and ultimately meltdown. The reactor can then only rely on passive safety systems such as the protective structure of the building and in some cases a "core catcher" to contain radioactive materials. If the protective containment structure also fails the release of radioactive materials can lead to Fukushima Daiichi and Chernobyl type disasters (Delta, 2009) (Rijksoverheid, 2010) (Krepel, et al., 2014) (World Nuclear Association, 2014) (World Nuclear Association, 2014) (World Nuclear Association, 2014) (World Nuclear Association, 2014).

Beyond design accidents – LFTR

In terms of severe accidents the LFTR clearly outperforms the PWR as meltdown and steam explosion are simply not an issue anymore (LeBlanc, 2009) (Kamei & Hakami, 2011) (Weinberg Foundation, 2013) (Serp, et al., 2014).

The LFTR's closest equivalent to a severe accident would be a salt spill, in which case the molten salt would rapidly form a protective crust and harden at around 500 ^{0}C, trapping hazardous substances inside. Only a limited area around the solid salt would be hazardous and clean up would be relatively easy (Hargraves & Moir, 2010) (LeBlanc, 2009) (Weinberg Foundation, 2013) (Konings, 2014) (Soon, 2014) (Kloosterman, 2014) It is extremely unlikely for fuel salt to escape the containment building however (Soon, 2014).

Risk control and response to calamities

In case of accidents, procedures to handle their occurrence are in place. In the PWR these are well established while in the LFTR these are more tentative. For a full description of these see appendix H2.

3.3.2.2. Comparison

Nuclear power plants are designed not to pose any significant danger to the environment during normal operation. The LFTR has an increased radiation risk during normal operation due to the continuous processing of its salt, but the design is such that these effects are limited to an area called the "hot zone". Fuel salt contains hazardous ingredients such as beryllium but these are familiar chemistry that is routinely used in other industries. LFTR is expected to produce more tritium than the PWR but less than heavy water reactors, and engineering solutions to this issue exist.

The LFTR relies on a passive safety system that automatically restores normal conditions in case of unwanted temperature increases, and the fuel salt is automatically drained into safe containment tanks if a shutdown is required.

In terms of severe accidents the LFTR clearly outperforms the PWR as meltdown and steam explosion are simply not an issue anymore. The LFTR's closes equivalent to a severe accident would be a salt spill, in which case the molten salt would rapidly form a protective crust and harden, trapping hazardous substances inside. Only a limited area around the solid salt would be hazardous and clean up would be relatively easy. Based on the significant reactor safety improvement, the following ranking was applied:

The Pressurized Water Reactor	**4**
The Liquid Fluoride Thorium Reactor	**1**
Wind	**0**

3.3.3. Spent nuclear fuel and radioactive waste[20] Weight: 5

3.3.3.1. The Pressurized Water Reactor

Nuclear fuel elements are the main source of the PWR's radioactive waste. After several years these have to be removed and either reprocessed in a facility to recover any reusable nuclear fuel, or sent to storage directly in case of an open fuel cycle.

An average 1000 MW_e PWR produces about 200-350 m^3 of low and intermediate level waste, and about 20 m^3 high level wastes from spent fuel annually. If the waste is reprocessed it is reduced to 3 m^3 of high level waste (World Nuclear Association, 2014).

The PWR produces two main categories of waste:

Waste type	Source	Storage method
Very low, low, and intermediate level waste,	Low level wastes: repairs and maintenance Intermediate level wastes: equipment removed from inside the reactor	Low and intermediate level waste: e.g. a rock tunnel operating repository 100 metres deep in bedrock at the plant site for final disposal Very low level waste: repository at ground level
High level waste	Spent nuclear fuel	Cool down period of 3-10 years in protected on-site water pools. Followed by interim (30 year) storage in dry storage containers. It is then placed into a final disposal site in copper canisters surrounded by clay, and put in deep holes drilled into the bedrock

Table 6: Nuclear waste categories and storage method. Source: (Fennovoima, 2014, pp. 6-7)

3.3.3.2. The Liquid Fluoride Thorium Reactor

A well-designed LFTR produces 35 times less waste than the PWR annually and 83% of what is produced reach stable natural uranium levels after just 10 years, 17% after about 300 years, and 0.01% is plutonium which requires long term storage. That amounts to about 100 grams of plutonium annually in the LFTR, versus 300 kg in the PWR (Juhasz, et al., 2009) (LeBlanc, 2009) (Hargraves & Moir, 2010) (Kamei & Hakami, 2011) (Serp, et al., 2014) (Krepel, et al., 2014) (World Nuclear Association, 2014).

[20] See appendix H3 for additional detail on this chapter

The figure below shows how much raw material is needed to produce the same amount of energy in a PWR as in a LFTR. (Hargraves & Moir, 2010).

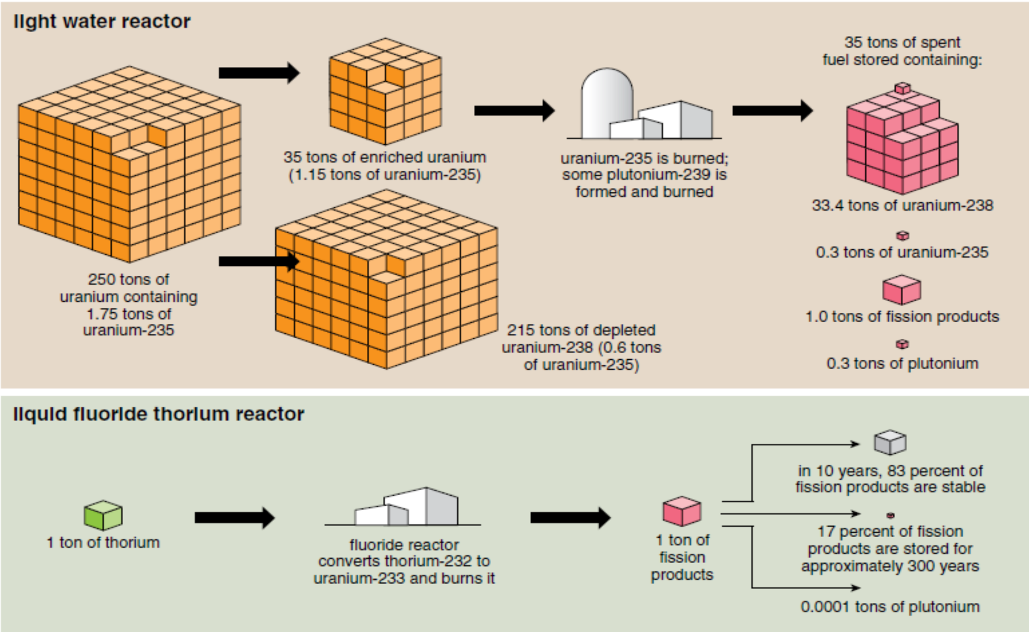


Figure 12: PWR vs LFTR fuel conversion rate. Source: (Hargraves & Moir, 2010, p. 308)

The reasons the LFTR has such a drastically improved waste production profile stem from its fundamentally different design. LFTR's are much better at converting fuel into energy than PWR's because they utilise all of their fuel instead of the PWR's 3-5%, and achieve a thermal to electrical conversion rate of 45-50% instead of the usual 30-37% (Hargraves & Moir, 2010) (Fennovoima, 2014). Unlike the uranium in the PWR, the LFTR's liquid fluoride fuel is not subject to radiation damage because of its strong ionic bonds. The fuel therefore does not have to be replaced every 1-2 years before all of it has been consumed, and fission products that are formed can simply remain in the fuel until they are completely burned up (Hargraves & Moir, 2010) (Hart, 2011) (Soon, 2014).

Disruptive fission products can also be easily removed from the fuel salt. An example is the gas xenon, which in solid fuelled designs remains trapped in the fuel's structure and disrupts the nuclear chain reaction, but in liquid fuel simply bubbles out of the solution (Hargraves & Moir, 2010) (LeBlanc, 2009) (Kloosterman, 2013). Fission products with commercial value can be sold while those without value can be safely stored (Soon, 2014).

In addition to producing almost no waste of their own, Molten Salt Reactors can be designed to greatly reduce or even eliminate existing stockpiles of actinide[21] waste, the main source of long lived nuclear waste (LeBlanc, 2009) (Hargraves & Moir, 2010) (Schaffer, 2013) (Serp, et al., 2014) (Krepel, et al., 2014) (Merk, et al., 2014). Molten Salt Fast Reactor designs seem especially suited to this task and are expected to be able to achieve an overall transmutation efficiency of 97% of all trans-uranium (TRU) elements and a burn-up of up to more than 90% of all plutonium isotopes (Merk, et al., 2014) (Krepel, et al., 2014).

The waste from a LFTR has a different composition from PWR waste but requires storage in geological repositories as well (Konings, 2014). It can be prepared for long term storage using vitrification[22] using borosilicate glass (Fig.13) (Soon, 2014). The expectation is that even if the entire world's energy demands were supplied by LFTRs only a few large repositories would suffice (Soon, 2014).

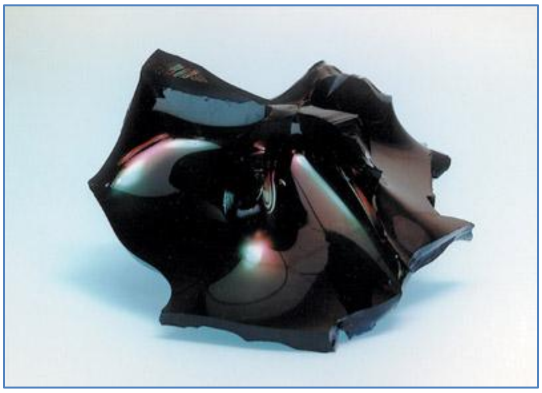


Figure 13: Vitrified nuclear waste. (DOE, 2001)

3.3.3.3. Comparison

The LFTR has a significant advantage over the PWR in terms of waste production. It produces about 35 times less waste in volume, and of what is produced 99.99% is safe within 300 years. There may still be a very small component that requires long term storage. What is more, MSRs can burn existing long lived waste. The following ranking was applied:

The Pressurized Water Reactor	**4**
The Liquid Fluoride Thorium Reactor	**2**
Wind	**0**

[21] Radioactive elements with atomic number 89-103 (Oxford University, 2014)
[22] Iimmobilization of waste by mixing it with a substance that will crystallise when heated such as sand or sugar, turning it into a rock-like glass (Health Physics Society, 2012).

3.3.4. Proliferation aspects Weight: 5

3.3.4.1. The Pressurized Water Reactor

Strict regulations have been drawn up to promote the responsible use of nuclear technology and to avoid nuclear material falling into the wrong hands under the International Atomic Energy Agency (IAEA)'s Non Proliferation Treaty (NPT). For the last 35 years it has been very successful in ensuring that uranium and plutonium are used for peaceful purposes only (World Nuclear Association, 2014).

To avoid the use of materials, technology or knowledge by bad actors, nuclear power plants only sign fuel contracts with installations that are under the supervision from international organisations like the IAEA or Euratom (Delta, 2009) (Rijksoverheid, 2010).

3.3.4.2. The Liquid Fluoride Thorium Reactor

Although theoretically possible, it is very difficult to use LFTRs to produce nuclear weaponry (LeBlanc, 2009) (Hargraves & Moir, 2010) (Kamei & Hakami, 2011) (Schaffer, 2013).

The thorium decay chain produces uranium-233 which is always accompanied by uranium-232. Uranium-232 is almost inseparable from uranium-233 and produces strong gamma radiation that is highly destructive to human beings, ordnance components, and circuitry (Juhasz, et al., 2009) (Hargraves & Moir, 2010) (Hart, 2011).

The quantity of free neutrons produced by LFTR further adds to its proliferation resistance. When uranium-233 fissions by absorbing a neutron, slightly more than two free neutrons are released. This is just enough for one of them to instigate the next fission reaction to keep the chain reaction going, and one to convert thorium-232 into uranium-233. If significant quantities of uranium-233 would be removed power generation would automatically decrease, which would not go unnoticed (Hargraves & Moir, 2010).

Producing nuclear weaponry would only be feasible for a party in full control of the reactor, and such an actor would have a far easier time simply generating plutonium or enriching natural uranium (Hargraves & Moir, 2010) (Kloosterman, 2013).

The LFTR can also play a role in reducing existing proliferation danger by burning plutonium waste from nuclear weaponry, turning it into energy and fission products that cannot be used to manufacture weapons (Rooyen, 2011) (Hart, 2011).

3.3.4.3. Comparison

Using PWRs for proliferation purposes is a common fear that is mitigated by making sure nuclear installations adhere to strict regulations that serve to avoid the use of materials technology or knowledge for proliferation purposes.

The LFTR has significant advantages in terms of inherent proliferation resistance compared to the PWR that has the potential to provide substantial relief in this important aspect. This resulted in the following ranking:

The Pressurized Water Reactor	**3**
The Liquid Fluoride Thorium Reactor	**2**
Wind	**0**

3.3.5. Cost of electricity & other economic factors — Weight: 5

Although not usually included as an "environmental impact", cost of electricity was added to this discussion because it is one of the "top 4" arguments against nuclear power. A summary of the broad economic characteristics for the three alternatives can be found in Table 7.

LFTR energy is expected to be significantly cheaper than the PWR's relatively expensive energy because of expected simplified and modular construction. Robert Hargraves expects LFTR energy to be cheaper than coal (2010, p. 310) (2012) and Ralph Moir comes to the same conclusion in his 2001 calculation of the MSR's cost of electricity (2001, p. 94). It is a largely theoretical technology however so until more progress has been made this cannot be said with certainty, something Moir suggests as well (2001, p. 94) (Kloosterman, 2013). LFTR's high operating temperature also makes it very suitable for additional processes such as hydrogen production and water desalination, and medical isotopes can be produced (Hargraves & Moir, 2010, p. 311) (Flibe Energy, 2014).

Onshore wind energy at prime locations produces at prices lower than hard coal plants already in Germany according to a 2013 Fraunhofer institute report. Offshore wind energy is about double the onshore price, caused by higher installation, operating, and financing costs. In the future offshore wind is expected to become more competitive, while onshore wind will convincingly fall below coal as coal prices increase (Kost, et al., 2013) (USEIA, 2014). The following ranking was applied to the technologies' cost of electricity:

The Pressurized Water Reactor	**3**
The Liquid Fluoride Thorium Reactor	**2**
Offshore Wind	**2**

	PWR	LFTR	Wind
Operational lifetime/years	60+	30-40+	20
Staff at peak construction	3500	Fewer due to modular construction	1000
Staff during operation	250	Strongly reduced	90
Construction time/years	9	Shorter	4
Approach to construction	On-site	Modular, largely off-site	Idem
Energy efficiency	37%	45-50%	Varies, 35-40% max
Plant surface area/MW	Small	V. small	V. large

Table 7: Other economic characteristics. For additional detail see appendix H4.

Sources: (EWEA, 2005) (Schlissel & Biewald, 2008) (Delta, 2009) (Juhasz, et al., 2009) (Watson, 2010) (Hargraves & Moir, 2010) (Wolters, 2011) (Boyle, 2012) (UCS, 2013) (Fennovoima, 2014) (Kloosterman, 2014) (Soon, 2014) (RWE, 2014) (London Array, 2014).

3.3.6. Emissions into air Weight: 5

3.3.6.1. The Pressurized Water Reactor & wind

A nuclear power plant does not produce large amounts of CO_2 as a result of its operation like fossil fuelled plants, but still releases certain pollutants into the air. These originate from multiple sources related to its construction, associated transport, auxiliary systems and emergency back-up systems such as steam boilers and generators, and as a result of activities along the nuclear fuel chain (Delta, 2009) (Rijksoverheid, 2010).

These activities contribute to the PWR's environmental impact and can be measured in the amount of CO_2 equivalent they generate. Including construction, operation, and all the activities in the nuclear fuel cycle a nuclear power plant was estimated to produce around 17 grams of CO_2 equivalent per kWh of electricity (g CO_2 eq/kWh$_e$) by Warner & Heath (2012, p. s73) in a Yale study that harmonised the result of 27 separate studies chosen for their quality from an initial set of 274.

Weisser (2006) made the following estimates for energy generation technologies:

Technology	g CO_2 eq/kWh$_e$
Current coal plants	950-1250
Future & advanced coal plants	750-850
Photovoltaics	43-73
Onshore wind	8-30
Offshore wind	9-19
Nuclear	2.8-24

Table 8: CO_2 equivalent output. Source: (Weisser, 2006, pp. 1550-1553)

It should be noted that Life Cycle Analysis estimates vary widely and are not without criticism as discussed by Beerten et al (2009). Nevertheless, this gives an indication of the differences between energy generating technologies, and shows that nuclear power produces roughly the same g CO_2 eq/kWh$_e$ as wind, less than photovoltaic installations, and much less than coal fired plants.

Radioactive gases created during reactor operation are captured and treated to reduce their radioactivity, after which they are released in a controlled manner. This ensures that levels of radioactivity always stay well below[23] the set limits and will be insignificant compared to naturally occurring background radioactivity (Fennovoima, 2014).

[23] The average annual radiation dose per person differs per country and is set at 3.7 milisieverts in Finland, while the planned reactor would always stay well below the set limit of 0.1 milisieverts a year (Fennovoima, 2014).

3.3.6.2. The Liquid Fluoride Thorium Reactor

Nuclear power plants produce small amounts of CO_2 equivalent already but this may well be even lower for the LFTR as a result of its simplified fuel chain and potentially easier construction. Its increased efficiency will spread CO_2 equivalent over a larger amount of kWh's as well. On the other hand some new activities will be introduced as part of LFTR's chemical component that are absent in PWRs (Hargraves & Moir, 2010) (Soon, 2014) (Konings, 2014).

The LFTR releases higher amounts the hydrogen isotope tritium than PWRs but less than heavy water cooled reactors and this can be safely handled (Weinberg Foundation, 2013) (Soon, 2014). A potential source of emissions could come from the helium used in the helium bubbling system for processing the fuel salt. After the helium had been used it has to be stored in a holding tank until any radioactive substances have sufficiently decayed and there may be releases from this source (Kloosterman, 2014).

The LFTR is not expected to release any other significant substances that could pose problems to human health or the environment into the air under normal operations. In terms of backup/auxiliary safety systems none are required for the core system but there may be a degree of redundancy built in for operational reliability. There will be a need for external power systems to reheat the drain tanks and re-prime the pumps and fuel system to restart a LFTR following a full shut down (Soon, 2014).

3.3.6.3. Comparison

Nuclear power plants produce relatively little CO_2 equivalent over the course of their life cycle, at a rate comparable to offshore wind. The LFTR could produce even lower amounts as a result of its simplified fuel chain and higher efficiency, although some additional activities related to the LFTR's liquid fuel will be introduced as well. Nuclear reactors release small amounts of radioactive gases such as tritium in a controlled manner during normal operation but this is expected to be mitigated in the LFTR design. A potential additional source of emissions could come from the helium used as part of the salt cleansing component. Because of these considerations the following ranking was applied:

The Pressurized Water Reactor	**2**
The Liquid Fluoride Thorium Reactor	**2**
Wind	**1**

3.3.7. Soil and groundwater[24] Weight: 2

3.3.7.1. The Pressurized Water Reactor

Construction could impact groundwater but not very significantly. During the operational phase there should not be any impacts on soil as potential dangers for contamination can be appropriately mitigated by technical means. Any wastewater from the controlled radioactive area of the plant is pumped to a liquid waste treatment system. The impact on soil and groundwater should therefore be relatively minor and only have an effect locally (Fennovoima, 2014).

Tritium and other radioactive substances dissolved in water are normally released by a nuclear power plant in a controlled manner (NRC, 2013).

Serious radioactive contamination of soil or groundwater is possible following an accident, as was seen in the recent Fukushima Daiichi disaster (World Nuclear Association, 2014) (Fennovoima, 2014).

3.3.7.2. The Liquid Fluoride Thorium Reactor

The most likely cause for contamination of soil and groundwater comes from the liquid fuel salt (Weinberg Foundation, 2013) (LeBlanc, 2009). In the event of salt spilling outside of the reactor, spilled salt passively solidifies and cannot be dispersed by wind. To prevent leaching into soil and water a protective barrier can be built around the reactor (Weinberg Foundation, 2013). Fission products are not volatile anymore so only leaking of the salt while still liquid is an issue, upon solidifying there is not much migration of radionuclides and it can be easily cleaned (Kloosterman, 2014) (Krepel, et al., 2014).

3.3.7.3. Wind

In addition to constructing the wind turbines, cables transporting the electricity from the offshore wind farm to where the electricity is needed have to be laid. On the on-shore stretch these are dug in over a wide corridor (54m)[25] which requires significant displacement of soil. To mitigate its environmental impact, soil can be stored separately and reinstated later to retain its integrity. Effects on groundwater and private water supplies should be negligible (RWE, 2011).

[24] See appendix H5 for additional detail on this chapter
[25] RWE example

3.3.7.4. Comparison

All three technologies have a potential impact on soil and groundwater resulting from their construction. Most large construction project will have these effects however and mitigating measures are available.

Beyond that the nuclear power plants employ mechanisms to ensure no radioactive materials can reach soil or groundwater during normal operations. Following accidents in PWRs there is a significant potential for radioactive contamination but this is strongly reduced in the LFTR. Only a small area in the direct surrounding of a spill would be contaminated which would lend itself well to relatively easy clean-up. The following ranking applies:

The Pressurized Water Reactor	**4**
The Liquid Fluoride Thorium Reactor	**2**
Wind	**1**

3.3.8. Cooling water discharges[26] Weight: 1

3.3.8.1. The Pressurized Water Reactor

In PWRs the steam that has gone through the turbine to generate electricity is to be cooled back down into liquid state by using cooling water which is discharged back into water it was sourced from at an increased temperature of about 10-12 ^{0}C.

The temperature impact from cooling water discharges on seawater was studied for the Hanhikivi EIA using a three dimensional flow model which showed that if the body of water that is discharged into is large enough the effects should be marginal and no significant adverse impacts on organisms are expected (Delta, 2009) (Rijksoverheid, 2010) (Fennovoima, 2014). See appendix H6 for additional detail.

3.3.8.2. The Liquid Fluoride Thorium Reactor

The LFTR is expected to make use of Brayton gas cycle turbines which enables a thermal to electric conversion efficiency of 45-50%, reducing the amount of cooling water per unit of energy required. In addition to that these turbines can rely entirely on air cooling, although water cooling will provide higher efficiencies. If there is a strong incentive to remove the environmental impact of cooling water at a given location this option would be open in theory (Juhasz, et al., 2009) (Hargraves & Moir, 2010) (Weinberg Foundation, 2013) (Soon, 2014).

3.3.8..3. Comparison

Nuclear power plants require large amounts of cooling water but the LFTR's higher efficiency reduces the amount required. In addition, using the Brayton cycle allows relying on air cooling if this were needed, at a slight efficiency loss.

The technologies were ranked as follows:

The Pressurized Water Reactor	**3**
The Liquid Fluoride Thorium Reactor	**2**
Wind	**0**

[26] See appendix H6 for additional detail on this chapter

3.3.9. Noise   Weight: 1

3.3.8.1. The Pressurized Water Reactor

Construction of the nuclear power plant may create noise pollution in surrounding neighbourhoods and mitigating measures should be taken (Delta, 2009) (Rijksoverheid, 2010).

Noise modelling for the Finnish nuclear power plant showed that noise levels would remain below accepted levels for residential areas during the construction phase as well as during operation. Very close to the reactor (construction) site noise levels could reach 50-53 dB (A) but at the nearest residence it would stay between 30-40 dB (A) (Fennovoima, 2014).

3.3.9.2. The Liquid Fluoride Thorium Reactor

The expected noise pollution from a LFTR facility during operation is currently largely unknown, but should not be a factor since the operation of the reactor and all its main components are expected to be underground. In the case of an aboveground reactor (which is not recommended) there is currently no data to suggest one way or the other (Soon, 2014).

3.3.9.3. Wind

Wind turbines have been perceived as noisy and a nuisance in the past but modern wind turbines are much quieter than their predecessors. At a distance of about 350 m a wind farm produces between 35 and 45 decibels of sound which is comparable to the noise from a busy road 5 km away (Fig.9). In Denmark the maximum allowed noise levels from wind turbines for open countryside are set at 45 dB, and 40 for residential areas. Noise can be reduced by lowering the rotation speed of the blades, or eliminating the gearbox in a wind turbine design (EWEA, 2005) (Boyle, 2012). Offshore wind turbines are generally built relatively far from shore however, which reduces the impact of noise to the closest residents even further.

Comparative noise for common activities	
Source/activity	**Indicative noise level (dB)**
Threshold of hearing	0
Rural night-time background	20-40
Quiet bedroom	35
Wind farm at 350m	35-45
Busy road at 5km	35-45
Car at 65km/h at 100m	55
Busy general office	60
Conversation	60
Truck at 50km/h at 100m	65
City traffic	90
Pneumatic drill at 7m	95
Jet aircraft at 250m	105
Threshold of pain	140

Table 9: Comparative noise for common activities. Source: (EWEA, 2010, p. 20)

3.3.9.4. Comparison

None of the three technologies produce much noise, although for the LFTR this is not certain yet. Wind turbines probably produce most noise during operation, but as they will be located at sea this is not likely to be a big nuisance. Construction may create considerable noise but this is shared with most large building projects. For specific developments the effects on neighbouring residents should be assessed and mitigating measures taken if needed. The following ranking applies:

The Pressurized Water Reactor	**2**
The Liquid Fluoride Thorium Reactor	**2**
Wind	**2**

3.3.10. Nature   Weight: 1

Environmental Impact Assessment requires indication of how the planned development may affect nearby locations of significant natural beauty or importance. Site specific issues will not be addressed but any items that can apply to wider site contexts are discussed (Delta, 2009) (Rijksoverheid, 2010).

3.3.10.1. The Pressurized Water Reactor

Potential effects on nature related to cooling water are sucking in fish and fish larvae, and discharging warm water which can affect natural habitats. A filter can be installed to mitigate these effects. Noise from pile driving and other construction can disturb habitats in terrestrial as well as aquatic surroundings. Toxic (radioactive) discharges may occur in case of (in-design) accidents. Tritium may be released but should not pose a threat to human beings or the environment, unless in high concentrations. Perhaps the effect is stronger on flora and fauna, which should be taken into account.

3.3.10.2. The Liquid Fluoride Thorium Reactor

Like the PWR, any of the LFTRs hazardous discharges could potentially have an effect on natural reserves and should be responsibly assessed for each location. Similar effects as described above are relevant and in addition to those, activities relating the fuel salt could present potential hazards while the effects of severe accidents are reduced.

3.3.10.3. Wind

Wind turbines have attained a degree of infamy for their effect on flying animal species[27] such as birds and bats. For offshore wind turbines there is an added impact on marine life such as fish, marine mammals, crustaceans, and others (Boyle, 2012).

While 573.000 birds collide with wind turbines each year in the U.S, 175 million collide with power lines and 300 million – 1 billion fly into glass surfaces according to the American Bird Conservancy (American Bird Conservancy, 2013). It could be argued that wind turbines are less prevalent than these other structures however. The Danish National Environmental Research institute carried out research on an offshore wind farm deliberately placed in an area that held a large bird population and found that there was no significant effect on waterbirds (NERI, 1998).

[27] Phase 2 of the London array was cancelled in 2014 due to concerns over waterbirds (BBC, 2014)

3.3.10.4. Comparison

Nuclear power plants can have an impact on the natural environment through cooling water intake and discharges. Construction activities and related noise can potentially disturb natural habitats for any large construction project. More serious damage to the natural environment could result from accidents and resulting large releases of chemicals and radioactive substances. In the LFTR this effect is much less pronounced due to its superior safety characteristics and reduced accident severity. Wind turbines are relatively harmless, perhaps with the exception of their effect on flying animals but this is contested.

The Pressurized Water Reactor	**3**
The Liquid Fluoride Thorium Reactor	**2**
Wind	**2**

3.3.11. Landscape, cultural heritage and geology Weight: 1

3.3.11.1. The Pressurized Water Reactor

Landscape & cultural heritage

The Borssele plant buildings would be approximately 60 metres high with a 100 metre ventilation shaft and would not include cooling towers (Delta, 2009) (Rijksoverheid, 2010). In addition to first the construction site and later the structure, the landscape will be impacted by construction traffic carrying large and heavy parts, and the roads needed to support these. Nuclear reactors may impact the cultural heritage of a landscape by not fitting in, which depends on the location (Fig.14).

Geology

If reactors are built in areas where the soil contains bedrock this may have to be blasted and removed. This is the case in the Hanhikivi EIA but not in the Borssele situation (Delta, 2009) (Fennovoima, 2014).

Figure 14: Nuclear power plant

Source: (Ecochunk, 2013)

3.3.11.2. The Liquid Fluoride Thorium Reactor

Landscape and cultural heritage

The LFTR's visual aspects are expected to be of lesser impact than the PWR's. The entire facility can be underground if need be, the only parts that have to be above ground would be the loading bay to access the concrete reactor chamber cap for ease of installation and removal of the core and other systems such as the off-gas system, and the main heat rejection stack. Even the stack filter can be located underground and the heat rejection stack can be made as high or low as practical. A 1GW plant would be no larger or higher than an average warehouse with a big chimney attached to it. In terms of visual appearance, there is a high degree of flexibility in architectural design, it can be as futuristic or non-descript looking as desired, since the only aboveground facilities would likely be offices for administrators (Soon, 2014).

Geology

If installations are to be built underground in areas where the soil consists of bedrock blasting and digging into bedrock will have increased relevance to the LFTR.

3.3.11.3. Wind

There has been considerable controversy over whether wind turbines fit into the landscape (Fig.15). The degree to which this applies depends on the size of the turbine, its design, colour, the amount of turbines, and the extent to which the movement of their blades attract attention, but also on the subjective opinion of the observer. Over time wind farms could also become more accepted as they become a more familiar part of the landscape (EWEA, 2005) (Boyle, 2012) (UCS, 2013).

Figure 15: Wind turbines in the landscape

Source: (Clevescene, 2013)

3.3.11.4. Comparison

Nuclear power plants are large structures that do not fit into every landscape due to their strongly heavy industrial appearance. The LFTR is expected to be largely built below ground and will therefore have a much smaller impact on the landscape. Wind turbines have a relatively strong impact on the landscape due to their height and the amount of turbines usually clustered together. The impact of this is subjective and dependent on the observer however. For offshore installations the problem is limited. The following ranking was applied:

The Pressurized Water Reactor	**4**
The Liquid Fluoride Thorium Reactor	**2**
Wind	**2**

3.3.12. Wastewater discharges

Wastewater discharges[28] are part of the EIA guidelines but neither PWR nor LFTR are expected to have significant adverse impacts associated with this (Delta, 2009) (Rijksoverheid, 2010) (Fennovoima, 2014). For detail see appendix H7.

3.3.13. Additional wind

3.3.13.1. Telecommunications and aviation

Wind turbines can potentially interfere with radar systems and aviation, depending on the siting of the array. This needs to be considered on an individual case basis and if relevant, mitigating measures implemented (RWE, 2011).The following ranking was applied:

The Pressurized Water Reactor	**0**
The Liquid Fluoride Thorium Reactor	**0**
Wind	**3**

3.3.13.2. Shipping & navigation

Wind turbine arrays can interfere with shipping and navigation and require a study of the potential effects on shipping and navigation in the development area, and measures that ensure continued safe shipping and navigation such as active vessel traffic monitoring and adequate marking and lighting of the array (RWE, 2011). Nuclear power plants could potentially impact shipping by their cooling water discharge or lighting, which has to be taken into consideration (Rijksoverheid, 2010) Cooling water discharge is expected to be lower in the LFTR.

The Pressurized Water Reactor	**2**
The Liquid Fluoride Thorium Reactor	**1**
Wind	**3**

[28] Other than cooling water, resulting from cleaning, rain, etc.

4. Impact evaluation

4.1. “Traffic light” summary matrix

The individual environmental impact rankings have been brought together in the table below to provide a quick total overview of the three technologies’ environmental impacts, as recommended for presenting impact results to decision makers (Glasson, et al., 2012, p. 135). A more sophisticated approach is the weighted impact matrix, which will be discussed in the following chapter.

The PWR clearly performs worst in terms of environmental impacts, wind performs best, and LFTR lies in the middle while leaning more towards the “good” side of the spectrum.

Criteria	**PWR**	**LFTR**	**Wind**
Technology characteristics			
Fuel cycle	Red	Yellow	Light blue
Transport	Orange	Yellow	Green
Construction work	Red	Orange	Green
Decommissioning	Red	Orange	Green
Top 4			
Nuclear safety	Red	Green	Light blue
Radioactive waste	Red	Yellow	Light blue
Proliferation	Orange	Yellow	Light blue
Costs	Orange	Yellow	Yellow
Environmental impacts			
Emissions into air	Yellow	Yellow	Green
Soil & groundwater	Red	Yellow	Green
Cooling water	Orange	Yellow	Light blue
Noise	Yellow	Yellow	Yellow
Effects on nature	Orange	Yellow	Yellow
Landscape	Red	Yellow	Yellow
Telecom & aviation	Light blue	Light blue	Orange
Shipping & navigation	Yellow	Green	Orange

Green	= Very good	=	1
Yellow	= Good	=	2
Orange	= Mediocre	=	3
Red	= Poor	=	4
Light blue	= No impact	=	0

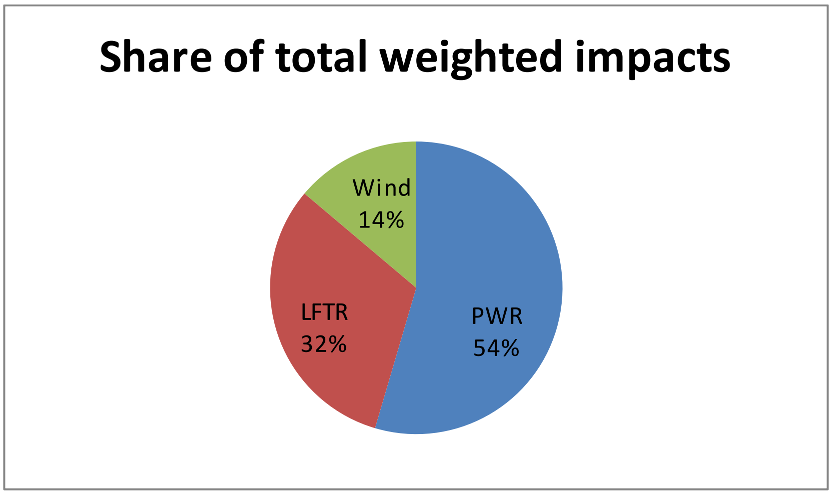
4.2. Weighted Impact Matrix

Because not all impacts can be considered to be of equal significance a weighting system has been applied to the simple ranking system. As the "top 4" impacts have been shown to carry the highest importance, and have a direct influence on nuclear policy and investors these were assigned the highest weights (5). The impacts of **fuel cycle** (3)**, transport** (2)**, emission into air** (4) and **soil and groundwater** (2) were assigned increased weights based on their perceived importance by relevant stakeholders according to the literature (Greenhalgh & Azapagic, 2009, p. 1060). For a justification of the weighting system see appendix C[29].

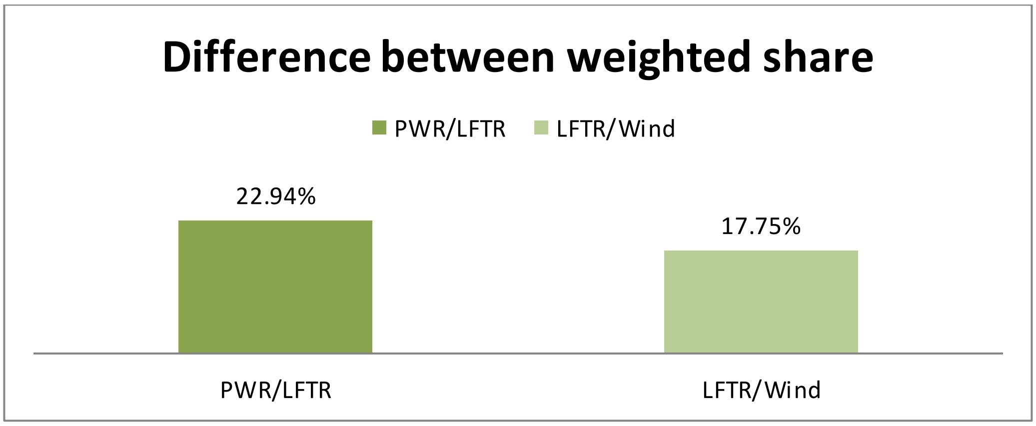
Criteria		Scores			Weighted Scores		
Technology characteristics	***Weight***	**PWR**	**LFTR**	**Wind**	**PWR**	**LFTR**	**Wind**
Fuel cycle	**3**	4	2	0	12	6	0
Transport	**2**	3	2	1	6	4	2
Construction work	**1**	4	3	1	4	3	1
Decommissioning	**1**	4	3	1	4	3	1
Environmental impacts - Top 4							
Nuclear safety	**5**	4	1	0	20	5	0
Radioactive waste	**5**	4	2	0	20	10	0
Proliferation	**5**	3	2	0	15	10	0
Costs	**5**	3	2	2	15	10	10
Environmental impacts							
Emissions into air	**4**	2	2	1	8	8	4
Soil & groundwater	**2**	4	2	1	8	4	2
Cooling water	**1**	3	2	0	3	2	0
Noise	**1**	2	2	2	2	2	2
Effects on nature	**1**	3	2	2	3	2	2
Landscape	**1**	4	2	2	4	2	2
Telecom & aviation	**1**	0	0	3	0	0	3
Shipping & navigation	**1**	2	2	3	2	2	3
Total scores		**49**	**31**	**19**	**126**	**73**	**32**
Combined total scores				*99*			*231*
% of combined total scores		49.49%	31%	19%	54.55%	31.60%	13.85%

[29] Statistical analysis of the weighted impact matrix was considered but is not expected to deliver statistically significant results due to the low amount of research units (technologies)

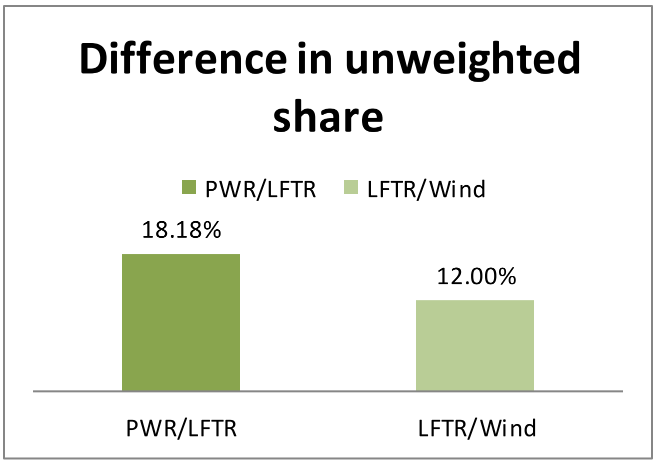
Analysis of the weighted scores shows that the PWR is responsible for more than half of total impact points, the LFTR for just under a third, and wind for about a seventh.

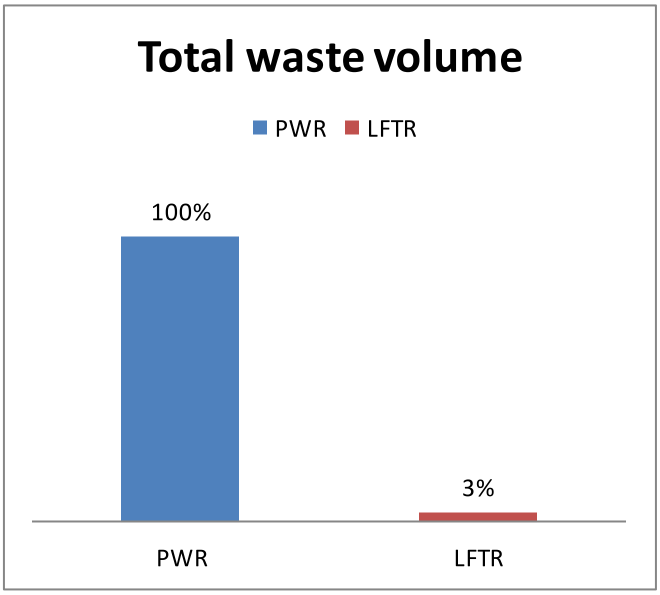


Analysis of the differences in percentages shows that the PWR scores almost 23% higher than the LFTR, while the LFTR scores close to 18% higher than wind, putting LFTR's environmental impact scores closer to those of wind than the PWR.



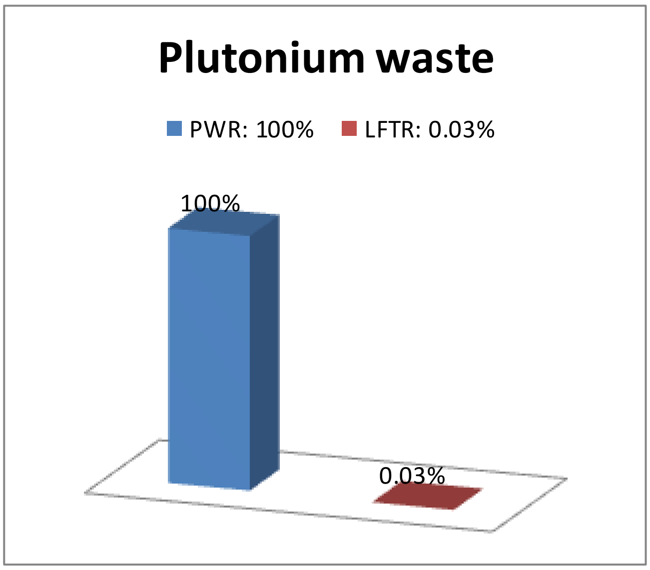
Weighting is based on subjective opinion but if we look at the outcomes without any weighting applied a similar pattern can be seen. The differences between the technologies do become smaller, as may be expected when items like nuclear waste, reactor safety, and proliferation are assessed in the same way as any other item. This puts LFTR's environmental impact scores slightly closer to wind, and slightly further away from the PWR with a drop of 6% and 5%, respectively.





Finally, nuclear waste production was not scored as "very good" because this was considered overly positive, as nuclear waste is still produced. The quantities produced represent such a vast reduction however that the 4 tiers do not do it sufficient justice. If the waste produced by the LFTR is represented as a percentage of the PWR's production volume, the charts on the left and below apply.

Overall the Environmental Impact Assessment clearly shows that the LFTR is expected to perform much better than the PWR in terms of environmental impacts. Wind power is still the most sustainable option, but the LFTR leans considerably towards wind's environmental impacts compared to the PWR.



5. Conclusions & recommendations

5.1. Realisation of aims and objectives

This research has yielded a transparent and comprehensive overview of the Molten Salt Reactor (MSR)'s expected environmental impacts. The amount of information that could be extracted from reliable literary sources was found to be substantial and additional information sourced from experts in this relatively novel field exceeded expectations. Existing EIA literature on the PWR and large scale wind power proved adequate to supply the information required to assess their relative environmental impacts.

After minor adjustments, Environmental Impact Assessment (EIA) generally lent itself well to setting the (LFTR) Molten Salt Reactor's expected environmental impacts against those of the Pressurized Water Reactor (PWR) and reasonably well to comparing them to large scale wind power, even though the technologies are essentially different.

5.2. Technology characteristics

The LFTR design is radically different from traditional nuclear power plant design. It uses liquid fuel instead of solid fuel rods and runs on thorium instead of uranium, which gives it very different properties from the PWR.

The thorium fuel chain has considerable advantages over the uranium fuel chain and thorium reserves are sufficient to satisfy the entire world's electricity needs for tens of thousands of years. This simplified fuel cycle also means that fuel and waste transport is reduced. LFTR construction and decommissioning may be easier due to the modular nature of the reactor but the chemical component presents additional complexity.

5.3. Alternatives

Many alternatives configurations exist for the PWR, the LFTR, and wind. All technologies come in different scales but the LFTR and wind turbines show the greatest range. For the nuclear technologies many different combination of fuel, coolant, moderator, plant lay-out, etc. are possible, each with slightly different characteristics.

Different locations will have different environmental impacts. Wind farms are restricted to areas that have sufficient wind resources, and can accommodate their size. PWRs can be built in many places but finding uncontested space can be problematic, and a large body of water is usually required. The LFTR shows potential flexibility as water is not necessarily required for its Brayton cycle turbine, and increased safety may simplify siting.

5.4. Environmental impacts

5.4.1. Top 4

The "Top 4" environmental impacts of nuclear waste production, reactor safety, and proliferation exhibited significantly different outcomes for the LFTR than for the PWR, and costs show potential differences as well.

Nuclear waste production will be drastically reduced in the LFTR. Total volume is expected to be 35 times less to produce the same amount of energy, and of what is produced 83% is stable in 10 years, 17% after 300 years and a 0.01% remainder requires long term storage. MSR's can also burn existing nuclear waste, which is something the Molten Salt Fast Reactor (MSFR) will be particularly suited for.

Reactor safety has improved to the point where serious nuclear disasters resulting from meltdown and steam explosion can be considered irrelevant. The closest equivalent danger is a fuel salt spill, which would require clean-up but has limited effect due to the fuel salt solidifying upon escaping its containment, locking dangerous fission products inside. An increased radioactive hazard stemming from the fuel salt processing facility exists during normal operation, but this is expected to be safely controlled.

Proliferation danger is strongly reduced due to the LFTRs physical unsuitability for weapons production. Although theoretically possible, the reactor is a poor means to this end. A party would have to be in control of the facility and would have a much easier time enriching natural uranium.

Costs of LFTR electricity may well turn out much lower than what is common for PWR's and will undercut coal according to some authors. Prudence dictates to refrain from stating this claim until the design is further advanced however.

5.4.2. Other environmental impacts

CO_2 *emissions into air* are low in nuclear power plants and expected to be even lower in the LFTR. Other emissions could result from tritium production and helium fuel salt processing but both can be safely contained.
Beyond their construction only the nuclear technologies have significant potential for contamination of *soil and groundwater* in case of accidents. While these could be very severe in the PWR, their effects are strongly reduced in the LFTR.
Cooling water could impact organisms during intake and discharge. LFTR's higher efficiency reduces the volume required, and the theoretical possibility of air cooling would remove the need for cooling water, although water cooling is preferred.

None of the three technologies produce much *noise*. Wind arguably produces more but for offshore turbines the impact is limited.
The PWR has the potential to have the biggest impact on *nature*, in case of accidents. In the LFTR the effects of accidents is strongly reduced. Wind is said to negatively affect flying wildlife but the significance of this is disputed.
Nuclear power plants do not fit into every *landscape*, but this is expected to be strongly improved in the LFTR due to much of the structure being below ground. Wind turbines' desirability as part of the landscape is contested, but out at sea this is less of an issue.
Finally, wind turbines can interfere with *telecommunications, aviation* and *shipping* which is something that has to be taken into account. Nuclear power plants' cooling water could impact shipping as well.

5.5. Conclusion summary

In summary, the results indicate that while the LFTR displays relatively positive environmental impacts overall, the effect is most striking in the top 4. Here is a technology that is expected to produce very little nuclear waste, provides greatly improved safety by removing the traditional dangers of nuclear power, shows considerable improvement in proliferation resistance, is believed to be much more economically competitive and can supply energy for tens of thousands of years. If the technology lives up to these expectations it represents a new low carbon, inexpensive, large scale source of energy with strongly reduced nuclear downsides. Considering that the world has been looking for alternative low carbon sources of energy but has a troubled relationship with nuclear power precisely because of these "top 4" disadvantages, and may not be able to solely rely on renewable sources of energy like wind, this technology has the potential to seriously shake things up and could provide interesting investment prospects.

5.6. Recommendations

Future work could contribute to this research in a number of ways. As this research was resource and time constrained, a full-scale EIA could be undertaken in the future. To enhance the EIA, the weights assigned to the environmental impacts can be based on advice from an interdisciplinary EIA team of experts. As LFTR technology research progresses the EIA results can be updated as well. Finally, as even experts in the field can be biased and are not infallible, this research could benefit from additional confirmation by other experts and reliable sources of literature.

Accurate information about what can be expected from a future technology like the LFTR is essential to making informed policy and investment decisions. To shed further light on this matter in order to understand the value of pursuing this potentially important development, it is in the interest of policy makers and investors to invest in additional research before fully committing. Environmental impacts are just one aspect of this large subject. The technology is relatively new and many areas beyond the purely technological research offer research opportunities that can help better inform future predictions. These include, among others:

- Deeper investigation of LFTR costs
- Large scale fuel salt production feasibility
- Associated industries like hydrogen production and (medical) isotopes
- Monetary savings from de-proliferation, carbon reduction, security measures, waste storage, etc.
- Maximum speed of deployment and potential resource constraints on large-scale deployment
- infrastructure requirements such as personnel and supporting industries
- Relevant international legislation and policy
- The potential role and resistance from the incumbent uranium industry

There is much left to find out about LFTR technology but what is known now holds great promise for the future. At the very least further exploration seems warranted to provide definitive answers to what is currently strongly suspected.

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Appendices

A. Why environmental considerations matter to nuclear power development

Nuclear power comes with controversial properties that have led to considerable debate about the desirability of this method of energy production.

The most commonly heard are the problems of safe (very) long term storage of nuclear waste, reactor safety, potential for nuclear weapons proliferation, and the relatively high costs of nuclear electricity (MIT, 2003) (Adamantiades & Kessides, 2009) (Greenhalgh & Azapagic, 2009) (Whitfield, et al., 2009) (Ahearne, 2011) (Teravainen, et al., 2011).

It stands to reason that a considerable improvement or complete removal of nuclear power's most significant downsides would take away important reasons for opposition to the technology. Other arguments could potentially be pushed forward by the most ardent opponents in the absence of the traditional ones but these are not likely to carry the same weight as the traditional top 4.

They have had a direct influence on national policies regarding nuclear power development as evidenced by Greenhalgh & Azapagic (2009) who examine the history of the UK's policy on nuclear power. They relate how in 1997 U.K. policy was not favourable towards nuclear power due to public unease following nuclear accidents at Three Mile Island and Chernobyl as well as concerns about waste disposal and decommissioning of nuclear power plants, making "…further investment in nuclear power an unattractive proposition". They go on to say that nuclear waste problems have been consistently raised as the main reasons for government not to engage in new nuclear development and conclude that government needs to address barriers to nuclear power or will continue to generate opposition and mistrust (Greenhalgh & Azapagic, 2009). Whether valid or not, people's reservation can potentially hamper pro-nuclear policy and slow down progress of new nuclear development (Dresselhaus & Thomas, 2001) (Adamantiades & Kessides, 2009) (Greenhalgh & Azapagic, 2009).

A more recent example where policy was directly influenced by nuclear power's risks was the reaction to the Fukushima Daiichi disaster. In Germany especially no half measures were taken by government who announced the immediate shutdown of eight of its nuclear power plants and a more gradual phase out of the remaining nine before 2022 in response to the events in Japan (Merk, et al., 2014). Prior to that Three Mile Island and Chernobyl had had a significant adverse impact on nuclear growth in the U.S. and nations across Europe. This is well captured in the often heard saying that goes: "A nuclear accident somewhere is a nuclear accident everywhere." (Ahearne, 2011)

An overarching barrier for nuclear power mentioned in the literature that is influenced by all of nuclear power's perceived negative properties is that of public perception (Dresselhaus & Thomas, 2001) (Adamantiades & Kessides, 2009) (Greenhalgh & Azapagic, 2009) (Whitfield, et al., 2009) (Ahearne, 2011). In democracies political decisions and stances are influenced at least to some extent by popular opinion and what constituencies want from their representatives. In addition to that, one issue with nuclear power that does not get solved partly because of public perception is that of long term nuclear waste disposal. Governments are having a very hard time finding locations for long term disposal because citizens understandably do not want a geological repository "in their backyard" (Adamantiades & Kessides, 2009) (Ahearne, 2011). This further inhibits a solution to the waste issue which in turn adds to the problem's persistence, which adds to negative public perception, etc.

A "Eurobarometer" study conducted in 2008 found that opinions for and against the use of nuclear power were about equally divided, but upon being asked what their opinion would be if the waste problem were to be resolved 39% of respondents that had indicated being against nuclear power said that this would change their mind (Greenhalgh & Azapagic, 2009).

Public opinion and political decision making are negatively influenced by nuclear power's undesirable properties. This will be a factor for investors considering financially backing the development of a new nuclear technology, as it represents a serious risk: they could be left empty-handed if the political leadership decides against the use of nuclear power in favour of other technologies, somewhere along the 10-20 year development trajectory. In the most extreme case it could mean zero return on investment because nuclear has been removed from the political agenda, but even a more conservative nuclear policy could mean a smaller potential for new nuclear development than expected, preventing investors from breaking even on their investment. This is corroborated by Greenhalgh & Azapagic (2009) who add that this is exacerbated by the fact that credit is harder to come by during the current financial crisis, making investors even more reluctant to commit.

In their 2009 article Adamantiades & Kessides identify reactor safety, nuclear waste management, and proliferation as the main barriers nuclear power has to overcome and state that advanced nuclear reactors are expected to address these and may therefore tip the balance in favour of nuclear power. In addition to "evolutionary" iterative designs which are improvements to existing older reactor types, these include the "generation IV" reactors. Gen IV represent six truly innovative designs deemed most promising by the international community that are often fundamentally different from earlier types, one of which is the Molten Salt Reactor (MSR) (Adamantiades & Kessides, 2009).

Finally, the sudden increase in MSR research around the world in recent years is telling in itself. Industry is aware of the traditional problems with nuclear power and seems to embrace this technology that promises solutions more and more (Krepel, et al., 2014). (Serp, et al., 2014) (Merk, et al., 2014).

B. Experts

The recent renewed MSR research interest is relatively new, and although research and publications on the subject are increasing with each year that passes, some information is still not easily accessible. It was decided therefore that the report would benefit from having information from secondary sources complemented by testimony from experts in this field. The questions were developed after analysing existing secondary sources for the information needed to comply with the guidelines for nuclear reactor Environmental Impact Assessment as set out by the Dutch government. Any information that was found lacking or unclear was added to the questions.

Three experts were contacted, a Dutch researcher specialising in nuclear physics working on the MSR at the Delft university of Technology, another Dutch researcher specialising in the chemical component of nuclear reactors and MSRs working at the Institute for Transuranium Elements (ITU) in Karlsruhe, Germany, and the business director of the prominent American start-up working on developing their own Liquid Fluoride Thorium Reactor design, Flibe Energy.

The method of gathering the necessary information from these experts that was employed was to first send them a list of around 25 questions, to allow them time to carefully consider their answers. The answers were then returned and processed and notes were made on any answers that required clarification or elaboration. A follow-up appointment was then made to discuss the questions and provide conclusive answers. The ideal method for the follow-up discussion was decided to be through chat instead of over the phone. The advantages are that:

- No recording has to be made. This can be preferable as experts can carefully weigh their answers and run less risk of inadvertently saying something they may regret
- It provides an instant written account, allowing experts to review what they have said
- It allowed the researcher to carefully interpret and fully understand the (sometimes very technical) answers before replying, which enabled a more thorough and higher quality discussion.

The exception was the interview with Kloosterman which was conducted over Skype and recorded, as he indicated preferring this method.

C. Scoring system

Assigning scores is very subjective and therefore susceptible to manipulation. If a slightly different approach to scoring is used, very different results can be attained. It is therefore important that this process is made transparent so the reader can read the justification and decide whether he or she agrees (Glasson, et al., 2012).

4 colours were used for the "Traffic light" ranking because in some cases LFTRs impact were such that it presented a great advantage over the PWR, but could not be said to be "ideal"/"very good". Green was therefore not appropriate, but to signify a true departure from PWR conditions some more distance had to be created. If just 3 tiers were used as in the classic traffic light, LFTR impacts would have to be ranked as exactly between the PWR and wind, which is too rough of an appraisal that does not tell the reader enough.

The number of tiers was kept to a minimum to enable relatively easy overview. Radioactive waste production required more nuance, but to adjust all the other categories to this exception's requirements went too far. An additional separate chart was therefore added to the matrices' discussion for the exceptions, so the observer can appreciate the extent of the difference.

C1. Rationale for ranking

Fuel cycle: The LFTR's thorium fuel cycle shows a significant improvement compared to the PWR's uranium fuel cycle. Wind does not have a fuel cycle.

Transport: Due to LFTR's simplified fuel chain significantly less (radioactive) transport is required than for the PWR. Wind does not require any fuel transport at all.

Construction work: Nuclear power plant construction is a large and complex task that has been known to run into considerable cost and schedule overruns. Construction could potentially be much easier in LFTR due to modular construction, but there is the added challenge of the chemical component. Wind turbine construction is a feat of engineering but significantly simpler.

Decommissioning: Decommissioning of nuclear power plants is a relatively difficult task. LFTR may possess advantages in this respect. Wind turbine decommissioning is relatively easy and does not involve any radioactive components that have to be dealt with.

Nuclear safety: Safety is a big concern in PWRs. Although unlikely, an accident has major consequences as was recently seen in the Fukushima Daiichi disaster. The LFTR departs radically from the PWR as meltdown and steam explosion, the two main concerns in PWRs are not an issue anymore. Accidents that could happen will have much less dangerous effects. For wind power although accidents could happen, these are limited and not comparable to a nuclear disaster.

Radioactive waste: The LFTR has strongly reduced nuclear waste production compared to the PWR and the vast majority of the waste remains hazardous much shorter. In addition to that, MSRs are capable or burning existing nuclear waste. Wind power does not produce nuclear waste.

Proliferation: Proliferation is a concern in the PWR that is mitigated by strict regulations. The LFTR presents significant benefits by being inherently unsuitable for nuclear weapons production. Proliferation does not apply to wind power.

Emissions into air: Nuclear power plants have low CO_2 equivalent production profiles. LFTR could perform even better in this respect but could potentially include some additional emissions. Although these are expected to be safe, the PWR and LFTR were ranked equally and wind was ranked slightly higher due to comparable CO_2 equivalent emissions but nothing besides these.

Soil & groundwater: All three technologies can have some impact on soil and groundwater through construction, but in case of accidents the PWR could have very serious negative impacts. The LFTR performs much better in case of accidents, but cannot be placed on the same level as wind which does not have any significant impact beyond construction.

Cooling water: Not as significant an impact as something like nuclear waste, so the worst performing PWR gets a "mediocre". LFTR scores higher because of the improved energy efficiency and associated lower cooling water discharge, and the theoretical possibility of using no water whatsoever. Wind uses no cooling water and thus attains a perfect score.

Noise: None of the technologies produces much noise. Wind arguably produces most, but as offshore turbines are out at sea this is issue is limited

Effects on nature: None of the nuclear technologies pose significant hazards to nature during normal operation. In case of an accident, results are severe in case of the PWR but these are very rare. For the LFTR even in accident situations effects are minimal. Wind power would get a perfect score if it wasn't for the supposed effects on flying animals and therefore scores "good".

Landscape: Nuclear power plants have a heavy industrial appearance and therefore do not fit well into every landscape. The LFTR is expected to improve greatly in this respect because it will be largely underground. Wind turbines are notorious for eliciting negative responses regarding their appearance, but for wind turbines located at sea this is less of an issue.

Telecommunications and aviation: Wind arrays have been known to interfere with radar and aviation. This is less of an issue for nuclear power plants.

Shipping and navigation: Offshore wind turbine arrays are large structures built at sea and can therefore impact shipping. Nuclear power plants can also have an effect on shipping but to a lesser extent, through lighting and cooling water discharges.

C2. Rationale for weighting

It was clear from various sources of literature that the "top 4" of nuclear waste, reactor safety, proliferation, and costs were the most significant impacts. Beyond that it would be helpful to assign relative importance to the other impact categories as well so these can be assigned a weighted score.

Information about their relative importance came from the article '*Review of drivers and barriers for nuclear power in the UK*" by Greenhalgh & Azapagic (2009, p. 1060) who describe an analysis by Butler et al (2007) of the responses to the UK's Department for

Business, Innovation, and Skills[30]' consultation about its white paper "Our Energy Challenge" (DTI, 2006). In this document organisations commented on nuclear power and the analysis identified 22 concerns about nuclear power and counted how often each was mentioned to get an indication of the perceived importance of an issue.

Excluding the "top 4" and concerns that do not apply to EIA categories, relevant items were:

Concern	**Mentions**
New nuclear capacity would not make much difference in reducing carbon emissions	67
Uranium resources are finite and not indigenous	47
Nuclear energy is not carbon neutral over its lifecycle	46
Health and environmental issues from radioactive discharges and doses	20

Radioactive discharges were mentioned 20 times, signalling a concern over radioactive emissions from nuclear power plants. This was interpreted to apply to discharges into *soil and groundwater*, as well as *emissions into air*. Both were therefore raised one point in rating to 2.

The issue of uranium being a finite resource was mentioned 47 times. This was interpreted to apply to the *nuclear fuel cycle* which was raised by 2 points to 3 due to being mentioned more than twice as much as radioactive discharges.

The issue of nuclear power's carbon emissions was mentioned twice, with one phrasing being mentioned 67 times and another 46. Because of this *emissions into air* was raised another 2 points on top of the radioactive discharges point to a total of 4 points.

To signal the "Top 4" as the most significant impacts, these were assigned 5 points each.

The authors mention that even though transport of nuclear materials received a low score, this is probably not representative. This is actually a very important issue but may not have been mentioned often because stakeholders believe its case has been established already in the past. Because of this, transport was assigned an additional point.

[30] Formerly DTI

D. Supporting tables

D1. Wind/nuclear comparison

Comparing 2 forms of nuclear power and one wind based technology will always be comparing apples with pears to some extent. Nuclear technologies have certain characteristics that are completely absent in wind power and vice versa, and it depends on the audience what value is placed on these.

An obvious example is the production of nuclear waste, which to some stakeholders is entirely unacceptable, while others may not be as concerned. One side may argue that any nuclear waste remains a hazardous burden for too long to be able to responsibly contain it, while the other may believe that strict regulations and technological advances will provide sufficient protection.

Because of the subjectivity of these matters a definite conclusion regarding the environmentally superior technology cannot be demonstrated beyond any doubt.

The more reasonable approach therefore would be to present the facts in the most objective and easily comparable manner possible, and let the reader decide.

To facilitate this, the EIA has been structured so that the aspects in which the three technologies do show similarity can be compared. Firstly, the LFTR's characteristics have been ordered and placed with the PWR's EIA items that match them most closely. Then offshore wind power's aspects that show similarity with PWR/LFTR categories been matched to these. The aspects of wind power that do not match any of the nuclear EIA categories have been discussed separately.

The table on the next page shows this structure.

Blue	= Comparison possible	**(12x)**
Green	= Unique to nuclear	**(5x)**
Purple	= Unique to wind	**(2x)**
White	= Very limited comparison	**(4x)**

PWR Categories	Relevant to LFTR	Relevant to Offshore Wind	Matching categories from wind EIA examples
Planned activity			
Technology description	Yes	Yes	Technology description
Safety principles	Yes	Very limited	
Fuel cycle	Yes	No	
Transport of fuel, waste and others	Yes	Yes	Traffic & transport
Cooling	Yes	No	
Construction	Yes	Yes	Construction
Decommissioning / Dismantlement	Yes	Yes	Decommissioning
Location alternatives	Yes	Yes	
Design alternatives	Yes	Yes	
Environmental effects			
Nuclear safety & radiation	Yes	No	Could include "normal operation"
Spent nuclear fuel & radioactive waste	Yes	No	
Risk control & response to calamities	Yes	No	
Proliferation	Yes	No	
Costs & economic	Yes	Yes	Socio-economic and other human activities (tourism) -Commercial fisheries
Emissions into the air	Yes	Yes	Air quality & CO_2 equivalent
Soil & groundwater	Yes	Yes	-Hydrology -Land and soil quality -Marine & coastal water quality -Ground conditions and

			water resources
Wastewater discharges	Hardly	Hardly	
Cooling water discharges	Yes	No	
Noise	Yes	Yes	Noise & vibration
Nature	Yes	Yes	-Marine ecology -Benthic ecology -Ornithology -Fish & marine life
Landscape, cultural heritage, geology & archaeology	Yes	Yes	-Land & seascape Geology -Archaeology (marine & terrestrial) -Cultural heritage
	No	Yes	Telecommunications, television, and aviation
	Somewhat	Yes	Shipping and navigation

D2. MSR information table

#	Safety - Pro	Safety - Con		Environment - Pro	Environment - Con
1	If the temperature rises, the rate of fission automatically decreases because the fuel expands, lowering the temperature (Weinberg Foundation, 2013) (Schaffer, 2013) (LeBlanc, 2009) (Serp, et al., 2014) (Krepel, et al., 2014)			LFTR produces virtually no long term waste and small amounts of short term waste (Weinberg Foundation, 2013) (Schaffer, 2013) (Kamei & Hakami, 2011) (LeBlanc, 2009) (Serp, et al., 2014) (Krepel, et al., 2014) Actinides are the main source of long lived waste (Hargraves & Moir, 2010)	
2	In case of large temperature increases a frozen salt plug at the bottom of the piping system melts and the fuel flows into safe containment tanks (Weinberg Foundation, 2013) (Krepel, et al., 2014) Power is needed to prevent reactor from shutting down (Hargraves & Moir, 2010)	Flibe's will not boil under normal operation but salt could boil in the core or catch basins during accidents. This could result in releases that need a mechanism (Krepel, et al., 2014)		Thorium will not require enrichment (Weinberg Foundation, 2013)	
3	Operation under atmospheric pressure eliminates the risk of pressure explosion (Weinberg Foundation, 2013) (Kamei & Hakami, 2011) (LeBlanc, 2009) (Serp, et al., 2014) Pressure in LWRs is the main cause for radiotoxicity (Krepel, et al., 2014)				Thorium mining involves processes involving sulphuric acid. I'm not sure how if this is a significant environmental impact or negligible (Schaffer, 2013)
4	Any spill would passively cool and harden (Weinberg Foundation, 2013) (LeBlanc, 2009) Would require several weeks clean-up (Krepel, et al., 2014) (Hargraves & Moir, 2010)			Thorium is already mined as a side-product of rare earths (Kamei & Hakami, 2011) 800 kg/ GWyear (LeBlanc, 2009)	
5	Meltdown is irrelevant b/c molten state is expected (Weinberg Foundation, 2013) (LeBlanc, 2009)			MSR's do not need water to operate and can be built away from water sources (Weinberg Foundation, 2013) Leblanc also	

				mentions the absence of water, but not sure if he means the entire system (LeBlanc, 2009)	
6	In the event of an attack on the reactor spilled salt passively solidifies and cannot be dispersed by wind. To prevent leaching into soil and water a protective barrier can be built around the reactor (Weinberg Foundation, 2013) (LeBlanc, 2009)				The MSR releases higher amounts of tritium than LWRs but less than heavy water cooled reactors. Tritium in high concentrations can be harmful to human health and under high temperatures it can penetrate metal barriers. The solution to this issue is expected to come from using the Brayton cycle which allow trapping tritium in gas (Weinberg Foundation, 2013) For FHR reactors that share the tritium issue the proposed solution is to 'capture tritium by forming yttrium tritide within double walled heat exchangers' (Serp, et al., 2014)
7	The fuel salt is continuously processed, removing dangerous fission products. This represents a slightly higher radiation risk during operation, but prevents these products releasing all at once in case of a severe accident (Weinberg Foundation, 2013) Advantage of 2-fluid design (LeBlanc, 2009) (Serp, et al., 2014) Fission products were main problem in Fukushima . Should adhere to same safety evaluations as reprocessing facilities (Krepel, et al., 2014) Plating and/or fluorination used to remove fission products (Hargraves & Moir, 2010)				According to Kloosterman when I spoke with him last year MSRs still produce a small fraction of very long lived waste. Kamei & Hakami seem to say smt similar but it is not very clear (Kamei & Hakami, 2011). Should inquire about this.
8	Schaffer mentions burial in rock or clay for "fission products" as adequate (Schaffer, 2013)	Suitable storage for separated fission products are under development (Weinberg Foundation,		MSR's can burn existing (actinide) waste (Schaffer, 2013) (LeBlanc, 2009) (Serp, et al., 2014) (Krepel, et al.,	

		2013)		2014) (Merk, et al., 2014)	
9	Thorium in the MSR is highly proliferation resistant for several reasons (Schaffer, 2013) (Kamei & Hakami, 2011) (LeBlanc, 2009)			Not exactly an environmental issue but honourable mention anyway: start-up fissile material may become an issue on large-scale implementation. Leblanc proposes solutions however (LeBlanc, 2009). Merk et al suggest starting up with plutonium and TRUs (Merk, et al., 2014)	
10	The European research effort plans systematic description of the components of the main systems around the reactor to identify potential accident initiators (Serp, et al., 2014)			Liquid fluoride solutions are routinely used in the aluminium and uranium industries. All uranium fuel has to go through a fluoride-form stage for enrichment (Serp, et al., 2014) (Hargraves & Moir, 2010)	Flibe is very toxic in general and contains Beryllium, a powerful carcinogen (No source yet) There was also mention of Lithium-7 being very hard to obtain, especially in large quantities and even potentially being a route to Lithium-6 and H-bombs
11	Both reactor and chemical plant licenses will be required (Serp, et al., 2014)			The thorium-uranium fuel cycle has a much better fuel burn-up ratio and thus resource utilisation (Serp, et al., 2014)	
12				No need to produce and transport expensive fuel elements (Serp, et al., 2014)	Flibe salt transport may be necessary if central production is chosen (Soon, 2014)

D3. Items in various wind power Environmental Impact Assessments

Loch Urr (E-on, 2012)	**Solwayback** (RES, 2011)	**EIA guidelines Serbia** (UNDP, 2010)	**Stoneton** (EDF, 2011)		**Teesside offshore wind farm** (EDF, 2004)	**Atlantic Array** (RWE, 2010)	**Thanet offshore** (RH/Thanet, 2005)
Landscape and visual impact	Landscape and visual		Landscape and visual amenity		Landscape and visual	Landscape and seascape	Land/Seascape and visual character
Ecology (non-avian)	Ecology		Ecology		- Marine ecology - Terrestrial ecology and nature conservation	- Benthic ecology - Ecology and nature conservation	- Marine ecology - Terrestrial ecology
Ornithology (birds)	Ornithology		Ornithology		Ornithology	Ornithology	Ornithology
Noise	Noise	Noise	Noise		Noise	Noise & vibration	Noise, dust and air quality
Hydrology, geology, and hydro geology	Hydrology, geology, and hydro geology	- Geology	Geology, hydrology, and hydrogeology		- Geophysical - Geology - Land and soil quality - Hydrology & hydrogeology	- Geology - Ground conditions and water resources - Hydrology & flood risk	- Hydrodynamics & geomorphology - Marine & coastal water quality
Archaeology and cultural heritage	Archaeology and cultural heritage	Archaeology & architectural heritage	Cultural heritage and archaeology		- Cultural heritage	- Marine archaeology - Terrestrial archaeology - Historic environment	- Marine archaeology - Terrestrial archaeology and cultural heritage
Transport and access	Access, traffic and transport		Traffic and transport		Traffic & transport	Traffic and transport	Traffic and access
- Aviation and radar - Telecom	Electromagnetic interference and aviation	- Interference with communication systems - Air traffic safety	Infrastructure, telecom, television and air safeguarding issues		Telecommunications, television, and aviation	- Military and civil aviation - Electric and magnetic fields	Radar and transmission systems
Shadow flicker	Shadow flicker	Shadow flicker	Shadow flicker		Shadow flicker		
Carbon calculations	Air and climate (emissions)		Air quality			Air quality	
Decommissioning		Decommissioning			Decommissioning, construction, operation	Decommissioning, construction, operation	
	Forestry	Natural heritage				- Fish and shellfish	Natural fish resource

						resources - Basking shark and marine turtles	
	Socio economics		Public access, amenity and socio-economics		Socio-economics, employment, and public attitude	Socio economics & tourism	Other human activities and socio-economics
	Health and safety	Safety aspects			Public safety	Marine mammals	Marine mammals
		Proximity to roads and railways			Commercial fisheries	Commercial fisheries	Commercial fisheries
		Proximity to power lines			Marine navigation risk assessment	Shipping and navigation	Shipping and navigation
		Windtake			Recreation	Recreation	Coastal tourism and recreation
					Coastal processes	Coastal and marine processes	
						Nature conservation	
						Military practice areas	
						Munitions	
						Marine aggregate extraction and waste disposal	
						Offshore oil and gas exploration	
						Offshore wind developments	
					Existing infrastructure	Subsea cables and pipelines	
						Soils, agriculture and land use	
					(cumulative effects)		

D4. Items in various nuclear Environmental Impacts Assessments

Borssele			**Oldbury (construction only?)**		**Guidelines EIA Rijksoverheid**			**Fennovoima**
Emissions/ radiation					**Nuclear safety and radiation**			
	Normal operation					Normal operation, events and accidents		
	Incidents					External calamities and accidents		
	In design accidents							
	Beyond design accidents							
Radioactive waste						Spent nuclear fuel and radioactive waste		**(Nuclear) waste management**
Chain approach to the fuel cycle								**Nuclear fuel production chain**
Proliferation related					**Proliferation**			
Atmosphere					**Air**			
	Emissions of nuclear substances							**Radioactive emissions into the air**
	Emissions of combustion gasses (NOX, CO_2, NO_2)							**Other emissions into the air**
	Emissions of particulate matter							
Soil			**Geology, hydrogeology and soils**		**Soil and groundwater**			**Soil, bedrock and groundwater**
	Presence of soil contamination							
	Potential for soil contamination							
Waste water discharge			**Surface water & flooding**		**Waste water discharges**			**Waste water**
	Quantity and composition							**Radioactive emissions into the sea**
	Impacts on quality of surface waters							
Discharge of cooling waters					**Cooling water discharges**			**Cooling water**
	Quantity							
	Impacts on biotic environment							
	Impacts on quality of surface water							

Noise & vibrations			**Noise and vibration**		**Noise**			**Noise**
	Noise during construction							
	Noise levels							
	Vibrations during construction							
Nature			**Ecology and nature conservation**		**Nature**			**Flora, fauna, and conservation areas**
	Impacts on protected species (flora & fauna)							
Landscape & visual aspects			**Landscape and visual amenity**		**Landscape**			**Landscape and cultural environment**
	Adverse impacts on landscape							
	Changes in visual aspects							
Cultural history & archaeology			**Archaeology and cultural heritage**		**Cultural heritage, geology and archaeology**			
	Adverse impacts on historical cultural aspects							
	Adverse impact on archaeological assets							
			Traffic & transport		**Nautical safety**			**Traffic and traffic safety**
			Air quality and dust[31]		**Risk control and response to calamities**			**Nuclear safety**
			Public access and recreation		**Cross border environmental effects**			**Construction of the nuclear power plant**
			Socio - economic		**Social and economic aspects**			**People and society**
					Gaps in environmental information			**Nuclear accidents**
					Monitoring and evaluation programme (uncertainty)			**Other abnormal and accident situations**
						Cooling systems		**Decommissioning of the power plant**
						Ventilation (Chimney)		**Trans boundary environmental impacts**
						Transport movements of material		**Cumulative?**
						Etc.		

31 An assessment of the potential air quality impact of emissions from construction and daily worker traffic on access roads would be undertaken, as would the effects of any rail or marine transport of materials.

E. Chapters excluded or amended in EIA guidelines

The exceptions that were excluded or amended will be briefly addressed here:

Introductory and general sections are condensed into one section outlining the instructions that have been applied, and omitting those that were discarded due to being too difficult or too detailed for this research' timeframe, or not relevant enough.

The comprehensive list of policies relevant to the Dutch Borssele reactor's development was moved to the appendix because although important in an EIA, it is less relevant to the purpose of this research and takes up a large amount of space.

The justification for building a nuclear power plant based on energy need, based on it being location specific.

Safety principles in the "planned activity and alternatives" section was left brief in favour of the "nuclear safety and radiation" chapter in the "Environmental effects" section

The location design and operation chapter was considered largely irrelevant because they are location specific. Relevant items from this section were therefore transferred to the "Choice of type of reactor section'.

The conventional installation section was excluded because it was deemed not to provide significant additional insight into environmental impacts beyond what is explained in other sections about reactor design, construction, and impact already. In addition, detailed information is not available for the MSR/LFTR as the final design is not even definite yet. Some general information regarding construction could be provided however.

From the "environmental effects" section, the "external accidents and calamities" chapter was omitted because it was considered redundant in light of the preceding section which describe accident situations sufficiently.

The "nautical safety" chapter was also omitted on the grounds that it is location specific and arguably of lesser environmental urgency. In addition, MSR/LFTRs effects on nautical safety can be assumed to be similar to the PWR or lesser.

The "Effects on Nature" chapter was partially omitted on the grounds of it being location specific as well. If and when specific MSR/LFTR developments are realised in the future, EIA's can take the impacts on local nature into account. These conditions will be different depending on the coordinates of a development, very different impacts can be expected in the Netherlands than Brazil for example depending on local species and conditions.

An EIA requires taking into account whether a site has archaeological significance. This will be site dependent however and was excluded.

The "Cross-border environmental impacts" chapter was entirely removed, based on it being location specific. It requires an explanation of whether any of the developments' effects are expected to transcend border, which entirely depends on how far the border is.

The EIA included a chapter listing policies relevant to the Borssele reactor development, this has been removed based on it being site specific.

F. EIA guidelines general requirements for “Environmental Effects” section

- It should always be stated if data is uncertain or unknown.

- When describing the environmental effects of the construction and operational phase, all sources of significant emissions should be identified including radioactive waste

- The significance of effect should be determined. Whether they are direct or indirect, positive or negative, their duration, scope, extent, reversibility, if there are cumulative effects, their likelihood of occurring, and their frequency

- The report should distinguish between effects that will occur during the construction phase, effects that will occur during the usage phase and effects that will occur during decommissioning/dismantlement and potential cross-border effects should be included

- Effect should be described quantitatively where possible

- Information should be presented in a way that is understandable to the general public

- When evaluating potentially dangerous effects conservative estimates should be applied

G. Planned activity supporting information

G1. Generation 3 reactors

The EIA guidelines require a description of generation 3 nuclear reactors. The planned reactor developments in Borssele and Hanhikivi are both third generation reactors (Delta, 2009) (Fennovoima, 2014).

Although nuclear reactors' basic operating principles have remained largely the same for decades, important iterative developments have been made over the years that have led to a substantially improved modern reactor design. The different improved versions in reactor development are referred to as "generations", and the most modern existing nuclear reactors belong to generation 3 (or 3+[32]) (World Nuclear Association, 2014).

Third generation reactors are characterised by improved safety, a higher degree of standardisation, a more robust and simpler design, a longer lifespan of around 60 years, a decreased chance of accidents, an improved capability of managing accidents in case they do occur, and an improved fuel utilisation leading to a higher efficiency (37%)[33] and a reduction of waste production (Delta, 2009) (World Nuclear Association, 2014).

Third generation reactor models include:

Westinghouse's AP600 and AP1000 Pressurized Water Reactors, 600 and 1000 MW of output respectively
Areva's 1600 MW European Pressurised Reactor (EPR)[34] based on designs bought from Siemens and incorporating experience from 96 reactors built by Framatome and Siemens
General 1600 MW Electric's Economic Simplified Boiling Water Reactor (ESBWR) that can be consider a generation 3+ design due to its high level of sophistication
Atomic Energy of Canada Ltd.'s 700 MW ACR7000 reactor design based on the CANDU heavy water reactor design but using heavy water only as the moderator and light water as the coolant
Areva's SWR1000 Boiling Water Reactor with a nominal capacity of 1250 MW
The VVER-1200, 1200 mW Russian Pressurized Water Reactor design

Table 10: Third generation reactor models. Source: (Adamantiades & Kessides, 2009, pp. 5157-5159)

[32] 3+ offers additional economics and safety improvements over generation 3
[33] In the Hanhikivi reactor example
[34] Also known as the Evolutionary Power Reactor (EPR)

G2. Thermal and fast MSR spectra

The difference between the thermal and fast spectra is whether the neutrons that cause nuclear reactions are left in their original "fast" state, or have been slowed down by a moderator to increase the likelihood of fission reactions occurring (Carpenter, 2003) (Konings, 2014).

The moderator used in thermal MSRs is usually graphite, which degrades in a neutron flux[35] and must be replaced after several years. Other materials such as zirconium hydride or beryllium oxide can be used as alternatives however. In the thermal version care has to be taken that the neutron economy[36] is suitable for burning. Fission products that disturb the neutron economy therefore have to be quickly removed, resulting in high demands for the salt clean-up process. The advantage of this is that the thermal MSR can work with a relatively small heavy nuclide[37] (Th,U) inventory and has smaller decay heat (Konings, 2014) (Kloosterman, 2014).

In the fast MSR actinides can more easily undergo fission and fission products do less harm because they do not absorb as many neutrons, resulting in lower processing requirements. A fast spectrum is therefore also better suited for burning existing actinide waste although it should be possible in principle to burn actinide waste in thermal spectra as well. There is a chance that not all actinides can be burned in a thermal spectrum, and a small number will be left at the end of the reactor's lifetime. It might be possible to use this residue to start up a new reactor, but it may have to be stored. A fast spectrum will put higher demands on materials however because of the fast neutrons that can easily damage structural materials. A thermal spectrum reactor should therefore be easier to accomplish (Kloosterman, 2014).

[35] Neutron radiation intensity (NRC, 2014)
[36] The "balance sheet" of how neutrons are utilised (Europe's Energy Portal, 2014)
[37] Nuclide containing additional neutrons (Oxford Reference, 2014)

G3. Uranium fuel cycle

Uranium mining can be done in underground or open mines. A third technique is by injecting hundreds of tons of ammonia, nitric acid and sulphuric acid into the ground which is pumped up after 3-25 years, yielding uranium. The mined uranium ore is then ground up into fine slurry in the milling process and placed in sulphuric acid for leaching. It is removed and converted into concentrated uranium oxide (U_3O_3), or "yellowcake" after which it is made into hexafluoride (UF_6) and placed in cylinders where it condenses into a solid. Uranium-235 is then removed from uranium-238 and enriched. Enrichment can be done either by gas centrifuge or gaseous diffusion, the latter requiring about 40 times more electricity. After enrichment the uranium is fabricated into fuel elements by sintering, baking, and finally pressing the uranium oxide into ceramic pellets which are stacked into fuel rods (Fthenakis & Kim, 2007) (Sovacool, 2008) (Lenzen, 2008) (Beerten, et al., 2009).

G4. Immediate dismantlement decommissioning

The Dutch government guidelines for the Borssele reactor indicate that the site must be left ready for future use (Rijksoverheid, 2010) which implies Immediate Dismantlement: Firstly the nuclear fuel (rods) as well as the coolant water that came into direct contact with these has to be removed. 99% of the radioactive hazard comes from the fuel while the remaining hazard comes from parts of the reactor that have been long exposed to radiation such as steel components. Some of their atoms have changed into isotopes such as iron-55, iron-59, and zinc-65 some of which emit dangerous gamma rays. They have short half-lives however, ranging from 45 days to 5.3 years which renders them largely safe in 50 years (World Nuclear Association, 2014). The advantage of Immediate Dismantlement is that personnel familiar with the reactor is available and existing equipment for handling radioactive materials can be used. The disadvantage is that removing the still highly radioactive materials is more complex and requires remote handling and shielding equipment, and it has to be brought to a facility elsewhere and stored (Knaack, 2012).

H. Environmental effects – Supporting information

H.1. Nuclear safety & radiation

H1.1. Normal operation – The Pressurized Water Reactor

Although it is theoretically possible for radiation from the power plant's buildings to come into contact with passers-by and local residents during normal operation, this radiation is much lower than naturally occurring background radiation levels and is limited to the immediate surroundings (Delta, 2009).

Small amounts of radioactive substances are discharged by the ventilation shaft during normal operation but these are much smaller than naturally occurring background radiation and extend over a very large area.

Even though radiation levels are expected to stay well below natural background levels, the radiation levels from both sources are carefully monitored to ensure they remain within safe concentrations. In addition to that any other processes likely to emit radiation such as processing or removing solid, liquid, or gaseous radioactive materials are monitored (Delta, 2009) (Rijksoverheid, 2010).

H1.2. Normal operation – The Liquid Fluoride Thorium Reactor

The majority of LFTR fission products are commercially valuable and will be stored for 30 day decay before being packaged and sold. The storage of volatile fission products does present a potential risk and this is something that must be considered, but this is largely mitigated by the design and containment of the reprocessing facility. The radiation risk is limited to within the containment boundary of the reactor facility in an area called the 'hot zone'. This area is off limits to personnel during operation of the reactor and actually constitutes the main sabotage resistance of LFTRs. The reprocessing plant could potentially be located below ground, below or next to the drain tanks, in a specialised zone that is designed to preclude the escape of volatiles. Externally there is no radiological hazard outside the containment boundary and with no motive force or source terms that could potentially damage the containment or propel radioactive material outside the containment, the danger to the environment and population is considered very low. Nonetheless as per good practice when dealing with all things nuclear, various detection systems could be placed around and within all LFTR facilities such as Geiger counters and Scintillation counters. Employees could all be equipped with dosimeters to measure exposure, and should have access to radiation purposed Personal Protection Equipment for daily operations. Emergency equipment such as remote handlers, shielding tarps and so on should be standard at all LFTR facilities (Soon, 2014). In general molten salt reprocessing facilities should adhere to the same safety evaluations as existing uranium fuel reprocessing installations (Krepel, et al., 2014).

H1.2.1. Liquid fuel

The liquid fuel can have multiple configurations of ingredients. A prominent one is "Flibe", containing Beryllium and Lithium. Beryllium is a carcinogen and Lithium is said to be relatively difficult to produce and obtain in large quantities (Halper, 2013) (Konings, 2014).

When in the chemical matrix of FLiBe, the hazardous nature of beryllium is less of a factor however because it is immobile. FLiBe is still toxic and must be isolated from workers as far as possible but this is routinely done in the aluminium and uranium industries where liquid fluoride solutions are widely used. In addition, all uranium fuel has to go through a fluoride-form stage before enrichment and is currently used in research reactors and considered for fusion reactors, making it familiar chemistry (Serp, et al., 2014) (Hargraves & Moir, 2010) (Konings, 2014) (Soon, 2014) (Kloosterman, 2014) (World Nuclear Association, 2014).

H1.2.2. Tritium

Tritium can be harmful to human health in high concentrations and can therefore become a problem if not properly addressed, particularly upon large scale LFTR deployment through cumulation. It can penetrate metal barriers under high temperatures (Weinberg Foundation, 2013) and its behaviour upon release to the environment is complex. Current tritium producing reactors are the PWR, heavy water cooled nuclear power plants, fusion reactors like ITER, and fuel reprocessing facilities (Filho, et al., 2013).

The MSR produces higher amounts of tritium than PWRs but less than heavy water cooled reactors which could release up to 20 times as much tritium as PWRs (Rho & Lee, 1998) (Filho, et al., 2013).

The solution to this issue is expected to come from using Brayton cycle gas turbines. The problem could be mitigated by keeping the tritium completely within the containment boundary. This is achieved by chemically trapping the tritium in the secondary loop before it leaves the containment boundary and the use of a closed cycle gas turbine ensures that even what little that somehow diffuses to the Power Conversion System (PCS) is trapped and removed (Weinberg Foundation, 2013) (Soon, 2014).

For FHR reactors that share the tritium issue the proposed solution is to 'capture tritium by forming yttrium tritide within double walled heat exchangers' (Serp, et al., 2014).

H.1.3. Events (malfunctions) – The Pressurized Water Reactor

"Events" are the lowest level of abnormal occurrences. An example could be the failure of the primary cooling system that transports heat from the core, or of the secondary cooling system that turns water into steam to provide adequate cooling, resulting in temperature increases. This causes the reactor's safety system to activate and restore normal conditions after which the reactor may be restarted and normal operations resumed. Events can occur several times during the nuclear plant's lifetime and do not result in radioactive discharges beyond licensed limits (Delta, 2009) (Rijksoverheid, 2010).

H.1.4. Events - The Liquid Fluoride Thorium Reactor

No additional information, see main body.

H.1.5. Design accidents – The Pressurized Water Reactor

No additional information, see main body.

H.1.6. Design accidents – The Liquid Fluoride Thorium Reactor

Flibe will not boil under normal operation but in fast reactor designs the salt could boil in the core or catch basins during decay heat removal accidents and release elements previously dissolved in the salt. The design can be such that it solves this issue however. The drain tanks need a passive heat removal system that removes heat to the environment (Krepel, et al., 2014) (Kloosterman, 2014).

H.1.7. Beyond-design accidents – The Pressurized Water Reactor

If the protective containment structure also fails the release of radioactive materials can have disastrous effects on the surrounding environment. This was seen recently in the Fukushima Daiichi accident and earlier in the 1986 Chernobyl accidents. Nuclear reactors are designed to be able to withstand the impact of aircraft crashing into it, earthquakes, shelling, acts of terrorism, and extreme elemental conditions like tsunami's, yet the Fukushima accident showed that a combination of circumstances could still prove capable of creating disaster (Delta, 2009) (Rijksoverheid, 2010) (Krepel, et al., 2014) (World Nuclear Association, 2014) (World Nuclear Association, 2014) (World Nuclear Association, 2014) (World Nuclear Association, 2014).

H.1.8. Beyond design accidents - The Liquid Fluoride Thorium Reactor

Firstly it should be noted that the traditional severe accidents associated with nuclear reactors - meltdown and steam explosion - do not apply to the LFTR.

In the LFTR the fuel is always expected to be in a molten state and the structure is engineered to accommodate this (Weinberg Foundation, 2013) (LeBlanc, 2009). What's more, the molten fuel salt has very different properties from pure molten solid uranium causing it to react differently if it were to escape its containment.

In the LFTR the coolant is the molten salt which does not boil below 1400 ^{0}C and therefore does not have to be kept under pressure, eliminating the threat of pressure explosion (LeBlanc, 2009) (Kamei & Hakami, 2011) (Weinberg Foundation, 2013) (Serp, et al., 2014).

If the molten salt's containment were to fail the salt would behave as a liquid and leak out into special catch basins. Upon escaping its containment the molten salt would rapidly[38] decrease in temperature and harden into an inert solid mass at about 500 ^{0}C. The molten salt contains no volatile species and before having completely solidified a crust rapidly forms that acts as a barrier to any hazardous materials escaping. Solid fuel salt is very heavy and could not be dispersed by the wind in the event of it spilling outside of the reactor containment. Only a limited area around the spill would be contaminated and clean-up would be relatively easy (Hargraves & Moir, 2010) (LeBlanc, 2009) (Weinberg Foundation, 2013) (Konings, 2014) (Soon, 2014) (Kloosterman, 2014).

It is extremely unlikely for fuel salt to escape the containment building however. For this to happen the protective structure around the core would have to be penetrated which would require a "bunker buster" type missile to be fired directly at it, which is only realistically conceivable in times of war. Flying an airplane directly into the structure would not penetrate it. The main external event that could be of significant concern is that of earthquakes, but this could be mitigated by seismic-isolation of the containment cell, which is something that a LFTR is very well suited for because it is a low pressure system using lightweight materials (Soon, 2014).

[38] The speed at which the fuel salt hardens depends on the quantity of the spill (Konings, 2014) but would take place within a reasonable timeframe from the occurrence of the spillage (Soon, 2014)

H.2. Risk control and response to calamities

H.2.1. The Pressurised Water Reactor

Severe accident management's objectives for Pressurised Water Reactors are to:

- "Terminate the progress of core damage once it has started
- Maintain the capability of the containment as long as possible
- Minimize on-site and off-site releases
- Return the plant to a controlled safe state" (Rajzrová & Jiřičková, 2013)

To achieve this, an initial strategy that is employed is to depressurize the primary water circuit to prevent and mitigate dangers associated with high pressure water. This strategy is well demonstrated and performed by a special depressurisation system, or a pressure relief valve in modern power plants. A further strategy to mitigate the effects of core meltdown is to inject fresh cooling water into the reactor. Although this can also have negative consequences, it is advised to do so as soon as possible as the dangers of not cooling the core override others. Another potential danger following an accident is the build-up of pressure inside the containment structure to such a degree that it cannot withstand it. To counter this, some of the materials inside the containment may be vented after radioactive materials have been filtered out, to reduce pressure. Finally, the accumulation and potential combustion of hydrogen is a significant danger that played a role in the Fukushima Daiichi disaster. Strategies to reduce this threat are catalytic recombination, inerting the containment atmosphere, or controlled ignition (Heck, et al., 1995) (Rajzrová & Jiřičková, 2013) (World Nuclear Association, 2014).

H.2.2. The Liquid Fluoride Thorium Reactor

The most plausible scenario would be the failure of a structural component leading to the leakage of fuel salt within the containment area since all active lines could come with integral catch pans or return pipe sheathing. The procedure would simply be for the operators to initiate a shutdown in the affected system (assuming a multiple core facility) and then flush the system using an unfuelled 'flush salt' similar to that used in ORNL's Molten Salt Reactor Experiment[39]. Once the requisite cool-down period has expired, a contamination scan could be initiated to ensure that radioactivity in the affected area has dissipated enough for personnel to go in and repair the damaged component.

A fuel spill where fuel salt would spill onto the actual floor is very unlikely since all active lines could have a double return sheath installed or be located above a catch pan. Should

[39] The experimental MSR built in the 1960's

that occur the procedure would probably be to let it cool and harden and then remotely clear the solid fuel chunks afterwards and commence a clean-up.

Fuel salt finding its way outside the containment boundary requires highly improbable scenarios, but in the hypothetical event of such an escape, there would need to be a cordon of the affected area as per standard in just as with any other hazardous material accident such as a chemical spill due to a road accident involving a chemical tanker truck. Frozen salt needs to be regarded as hazardous material that will require specialised Hazmat handling procedures and equipment and should not involve direct handling by personnel, even after the recommended cool-down period. In such an event direct exposure would be a concern and the first recommendation would be to cover the spill with a special shielded tarp until the material can be removed. There is less concern about widespread propagation since the radioactive material is immobile (Soon, 2014). Clean-up would probably require several weeks (Krepel, et al., 2014).

H.3. Spent nuclear fuel and radioactive waste

H.3.1. The Pressurized Water Reactor

The PWR produces two main categories of waste:

1. Very low, low, and intermediate level waste, Low level wastes from repairs and maintenance, and intermediate level wastes from equipment removed from inside the reactor
2. High level waste or spent nuclear fuel

The basic method of handling radioactive waste is permanent isolation from the environment

Solid waste is first sorted and its volume decreased by compression and thermal cutting as much as possible, and liquid and wet waste is dried and solidified in cement after which it is stored in 200 litre drums. Low and intermediate level waste can be stored in a rock tunnel operating repository 100 metres deep in bedrock at the plant site for final disposal. Very low level waste may also be stored at a repository at ground level.

The high level spent nuclear fuel waste will first be allowed to cool down for 3-10 years in on-site water pools protected by reinforced concrete structures. From there it will be packed in special dry-storage containers and moved to interim (30 year) storage after which it will be placed into a final disposal site. In the final disposal site the spent fuel will be placed in copper canisters surrounded by clay, and put in deep holes drilled into the bedrock (Fennovoima, 2014).

H.3.2. The Liquid Fluoride Thorium Reactor

The reasons the LFTR has such a drastically improved waste production profile stem from its fundamentally different design.

Unlike the uranium in the PWR, the LFTR's liquid fluoride fuel is not subject to radiation damage because of its strong ionic bonds. The fuel therefore does not have to be replaced before all of it has been consumed, and fission products that are formed can simply remain in the fuel until they are completely burned up (Hargraves & Moir, 2010) (Hart, 2011).

Disruptive fission products can also be easily removed from the fuel salt. An example is the gas xenon, which in solid fuelled designs remains trapped in the fuel's structure and disrupts the nuclear chain reaction, but in liquid fuel simply bubbles out of the solution (Hargraves & Moir, 2010) (LeBlanc, 2009) (Kloosterman, 2013). Fission products with commercial value can be sold while those without value can be safely stored. The majority will become inert within 30 years while 17% will need to be stored for a maximum of 300 years (Weinberg Foundation, 2013) (Soon, 2014). A possible storage method for fission products is vitrification, the immobilization of waste by mixing it with a substance that will crystallise when heated such as sand or sugar, turning it into a rock-like glass (Health Physics Society, 2012).

H.4. Social and economic effects

H.4.1. Operational lifetime

The operational lifetime of a PWR is expected to be at least 60 years (Delta, 2009) (Fennovoima, 2014) and fuel rods need to be reconfigured and replaced every 1-2 years (Soon, 2014). Because research is ongoing the LFTRs precise lifetime is not yet known. Theo Wolters mentions on the Dutch "Climategate" blog that a 30 year MSR core lifetime has supposedly been demonstrated (2011) and Jan-Leen Kloosterman states earlier versions may last 40 years, which could be extended if the system is still in good working order by that time (Kloosterman, 2014). The expected lifetime of an offshore wind turbine is about 20 years (RWE, 2014).

H.4.2. Employment

The three energy generating technologies also have an effect on employment. The PWR provides employment during construction for a period of around 10 years, with about 3500 people at the height of construction (Schlissel & Biewald, 2008) (Fennovoima, 2014). The current Borssele reactor employs around 250 people during normal operation and even more when fuel has to be changed (Kloosterman, 2014). LFTR is expected to require much fewer people during construction and operation. Staffing could consist of 3-10 people during operation. Multiple facilities could share some of the staff functions which could further so the average number of employees per reactor would decrease with greater deployment. What's more, if modular construction would take place elsewhere it would not benefit the local economy of the reactor site as much (Soon, 2014). Offshore wind turbine construction lasts around 4 years and employs a thousand people at the height of construction. During operation roughly 90 people are required (London Array, 2014) (London Array, 2014).

H.4.3. Efficiency

LFTR is expected to be able to reach a 45-50% thermal to electrical energy conversion instead of the 37% of the Hanhikivi example (Juhasz, et al., 2009) (Hargraves & Moir, 2010) (Fennovoima, 2014). Wind turbines' efficiency fluctuates depending on wind speeds and model, but can reach around 35-40% maximum efficiencies (Watson, 2010).

H.4.4. Energy density

Nuclear reactors produce much more energy per surface area occupied. An important environmental characteristic of wind farms is the amount of space they take up compared to others forms of energy generation. Wind turbines can be very large and because of their relatively low individual power output many are usually grouped together in arrays, taking up large amounts of space. This is arguably less of a concern for offshore wind farms than onshore, depending on the location (EWEA, 2005) (Boyle, 2012) (UCS, 2013).

H.5. Soil and groundwater

H.5.1. The Pressurized Water Reactor

Large construction projects require excavation and other activities that may impact the soil, such as the use of chemicals like lime that are added to the soil as binding agents to improve its strength. Accidental spills of chemicals used indirectly for construction could also potentially have an impact.

Construction could impact groundwater but not very significantly. Possible impacts are a lowering of the volume of groundwater due to construction and excavation of a site, and a change in the quality of the groundwater may result from explosives used for excavation not exploding and dissolving into groundwater for example, which can be mitigated by using explosives that are not easily soluble.

During the operational phase there should not be any impacts on soil as potential dangers for contamination can be appropriately mitigated by technical means. Concrete that comes into contact with groundwater may lower its pH value but only in the immediate vicinity of the structure. To protect against contamination of soil or groundwater underground structures can be cast from waterproof concrete. Waste water from the plant is filtered for oil and directed to the plant's wastewater treatment plant. Any chemicals onsite are stored in special containers appropriately labelled and in the case of a leak the premises containing the chemicals is drained into shielding and neutralisation pools (Fennovoima, 2014).

H.5.2. The Liquid Fluoride Thorium Reactor

No additional information, see main body.

H.5.3. Wind

In addition to constructing the actual wind turbines, cables transporting the electricity from the offshore wind farm to where the electricity is needed have to be laid. On the on-shore stretch these will be dug in over wide corridor (54M) which requires significant displacement of soil. To mitigate the effect on the soil it can be stored separately and reinstated later to retain its integrity. Where the cables run through agricultural lands an assessment of the soil quality is required. In the UK land can be classified on a scale of 1 to 5 under the MAFF Agricultural Land Classification System. During construction and for some time after the land can temporarily not be used. Long term effects on land quality would be limited to where cable jointing bays and a substation are built. Effects on groundwater and private water supplies should be negligible (RWE, 2011).

H.6. Cooling water discharges - The Pressurized Water Reactor

The temperature impact from cooling water discharges on seawater was studied by the Fennovoima EIA using a three dimensional flow model. The findings were that seawater would increase about 1 ^{0}C in an area of 15 km^2 surrounding the discharge and by 5 ^{0}C in an area of 0.7 km^2 surrounding the discharge. It would be limited to the seawater surface and not go deeper than 4 m.

Cooling water discharge does not have any effect on zooplankton but would stimulate the growth of water vegetation and filamentous algae in the 15 km^2 area. No adverse impacts on benthic fauna is expected nor is anoxia in deep waters or problematic increases in blooming of cyanobacteria.

The water's continued suitability has to be monitored and care has to be taken that changing circumstances such as additional facilities discharging cooling water or global warming do not compromise the water's effectiveness as a coolant (Delta, 2009) (Rijksoverheid, 2010) (Fennovoima, 2014).

H.7 . Wastewater discharges

H.7.1. The Pressurized Water Reactor

Wastewater discharges concern water discharges from the plant except for cooling water. These include rainwater, scrubbing, leaking and rinsing water, demineralised water regeneration residues, and groundwater used during construction work.

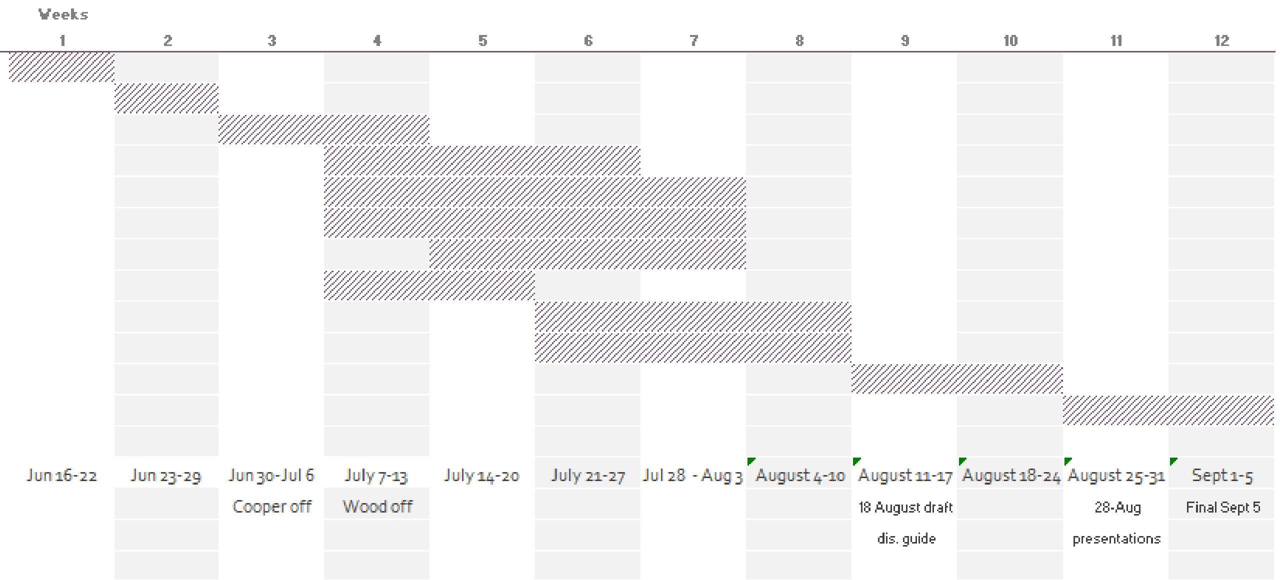
Demineralised water regeneration residues are treated to remove any radioactive substances after which these are stored, and the water discharged in surface waters (Delta, 2009) (Rijksoverheid, 2010). All waste water will be treated in a waste water treatment facility if necessary or discharged into the sea (Fennovoima, 2014).

H.7.2. The Liquid Fluoride Thorium Reactor

Waste water should be limited to normal sanitation waste from restrooms, showers, etc. Nothing that enters the containment zone is supposed to be discharged without proper filtering, analysis, and clean-up. This is dependent on what the final design will be however and not yet known (Soon, 2014).

I. Project planning – Gantt Chart

ACTIVITY	START	DURATION
LCA literature study	1	1
Project focus change to EIA	2	1
EIA project scoping/definition	3	2
Literature review MSR theory	4	3
Literature review EIA theory	4	4
Wind & Nuclear EIA's analysis	4	4
Literature review decision making	5	3
Scope LFTR EIA	4	2
Primary data collection	6	3
Populate/conduct LFTR EIA	6	3
Write-up	9	2
Buffer	11	2



J. Supporting documentation – CD

The CD submitted with this report contains a file with supporting documentation that was not considered directly relevant to reading this report, but is relevant to the overall work by providing evidence of:

- Supervisor meetings
- The expert questions and answers & follow-up chat conversations