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Molten Salt Reactors

The new frontier of nuclear reactors

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The aim of this paper is to present an alternative view on the prospect of nuclear power. Through analysing the history, current developments and the limitations of current nuclear technologies, it is possible to gain a broader understanding of the subject and raise awareness regarding our energy needs in the future. Moreover, due to predicted increases in energy demand, future generations will be at the mercy of technological advancements more than ever before.

Fossil fuels play a large role in providing the world with a cheap and abundant source of energy. However, their consumption comes at a price; the climate is changing due to our activities, thus a change in course is needed. While nuclear energy has been around for a long time, its development has been slow due to an abundance of cheap fossil fuels and it has seen much adversity due to its perceived dangers. Indeed, this is one factor that affects the adaptation of nuclear energy, including potential future investment.

Regardless of opposition, nuclear energy is one of the safest and most stable forms of energy production. The accidents that have occurred, have burned an incomplete and distorted image regarding the dangers of nuclear power. However, statistically speaking, nuclear power has the lowest death-rate per terawatt-hour (TWh) due to releasing almost zero greenhouse gasses whereas, burning fossil-fuels indirectly causes the deaths of hundreds of thousands of people every year. Currently, nuclear power provides the world around 11% of its power requirements, whereas, the majority still is provided by burning of fossil-fuels.

New technologies such as the development of Molten Salt Reactors (MSR) are being researched in order to improve the safety, reliability and sustainability of nuclear reactors. Indeed, the foregoing of water as a coolant is one of the greatest steps being taken in nuclear safety. Moreover, MSR's are expected to be much more economical to build compared to current designs due to their smaller physical footprint and simplified safety features which add to their value compared to other sources.

In the future, these technological advancements are invariably going to play an essential role in helping to solve the global climate crisis. The global population is expected to rise to 8.7 billion by 2035 which is going to put a strain on resources and the need for access to clean water and electricity. Indeed, world electricity demand is expected to rise from the year 2011 to 2035 by 81% and this demand must be met via carbon-neutral methods if the goals for sustainability are to be met.

This thesis takes an in-depth look at current and future nuclear technologies, their cost competitiveness compared to other sources and their impact on sustainable development for a greener future.

Keywords	Uranium, Nuclear Energy, Fast-Breeder Reactor, Molten Salt Reactor, Sustainable, Renewable, Electricity, Global Warming, Cost Competitive

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List of Abbreviations

MSR	Molten Salt Reactor
MWe	Megawatt electric
TWh	Terawatt hour
NPT	Nuclear Non-Proliferation Treaty
GWe	Gigawatt electric
kW	Kilowatt
LWR	Light Water Reactor
HWR	Heavy water reactor
BWR	Boiling Water Reactor
PWR	Pressurized Water Reactor
LFTR	Liquid Fluoride Thorium Reactor
U-234	Uranium-234
U-235	Uranium-235
U-238	Uranium-238
U-239	Uranium-239
Pu-239	Plutonium-239
Th-232	Thorium-232
UF6	Uranium Hexafluoride
GHG's	Green House Gasses

1 Introduction

Throughout history humans have had to rely on energy from different sources in order to survive and develop. This energy, typically in the form of fossil fuels has been extracted from sources such as wood, coal, gas and even whales were hunted for the oil within their bodies before the invention of petroleum. Through this process, which has been on-going for thousands of years, humans have been able to develop from cave-dwelling primitives to the modern intellectuals they are today.

Although fossil fuels still today provide the core of our energy needs, through one of human's greatest milestones, the splitting of the atom, humans were able to develop an energy source which could be used for both destructive purposes or to grant civilization infinite power - or so it was believed. Indeed, the Atomic Age was characterised by an era of overwhelming admiration for everything nuclear, however, this dream was short-lived due to misunderstanding and the potential for terrible misuse.

As one of the most potent energy sources available, it is ironic that nuclear energy has not developed much since its inception in the 1950's. Naturally, the technology has adapted to new developments as our understanding has improved, but most of the designs in use still today have their roots in the short but vivid years of research.

The concept of splitting the atom may seem complicated but generally speaking the process is quite simple, and indeed is one of the reasons why the designs have not changed much. However, interest in nuclear technology has been picking up once again due to the realization of the frailty of the environment and the climate which it supports. Events such as the Fukushima-Daiichi accident in Japan have spurred research into new designs for nuclear reactors, namely Molten Salt Reactors (MSR) which use a salt-mixture for cooling the reactor instead of pressurised water. This concept is not new, but includes many advantages of safety, sustainability and nuclear non-proliferation over older legacy designs which utilize water for cooling the reactor.

These new reactor designs could be used in tandem with renewable sources of energy such as wind, solar, geothermal and others to help alleviate environmental problems caused by the burning of fossil fuels. As nuclear energy and especially MSR's have an extremely low carbon footprint, they can act as base-load providers of clean energy. Compensated by renewable sources for peak-hours, these different but highly important sources of energy lead to a positive energy mix which should be the goal of any nation that wishes to cut down on its carbon footprint. Indeed, as the earth's population will grow leading to further urbanisation, the demand for access to electricity and clean drinking water will also increase. In order for developed and developing nations to reach carbon neutral goals, better options must be made available for clean energy generation. Molten Salt Reactors are one of these options, however, they are still in the development phase and require more research, investment and a willingness to a take fresh look at nuclear energy as a safe and sustainable way to reach carbon neutral goals.

1.1 Research Problem

The question whether nuclear power is a viable long-term source of power has been debated for a long time. Ever since its inception, it has received much appraisal and criticism for its ability to generate large amounts of power at high capacity relative to other forms of electricity generation, however, the factors of nuclear waste and the damage that it can potentially have on the environment need to be considered. Furthermore, nuclear power plants are extremely expensive projects to complete therefore, considerations of the opportunity cost for the time and resources placed into the project need to be considered as well, relative to other projects naturally. However, due to these factors and the increasing concern for the climate, focus has shifted into developing greener alternatives including the development of nuclear reactors which are capable of delivering the same amount of power as before but with added safety features and sustainability for the future in mind. Thus, this paper will focus on the history of nuclear reactors as an introduction, detail the economics behind current reactor designs and introduce and analyse future reactor designs including their potential to generate clean and sustainable energy.

1.2 Research Questions

The following questions will be addressed in one form or another during the course of this paper:

- What is the state of current nuclear reactors today and what challenges do they face?

- Can nuclear energy compete with other sources of power?

- New reactor designs have been around for a while now. What challenges do they face and can they change the perception that people have on nuclear energy for the better?

- Considering the future of human civilization, especially through the impact that global warning has and will have, can nuclear energy be used as a sustainable and eco-friendly way to generate energy?

1.3 Research Methodology and Ethical Issues

For this paper, mostly primary and secondary online sources were used. The research conducted was done so thoroughly in order to acquire the most up-to-date information available. Although information of current reactors, their capacities and economic factors can be found in books, much of the information was readily available on the websites of organisations which collect this type of information and update it regularly, hence it is a superior source of information.

Moreover, this paper includes sources from several studies which were found online, and were a great source of knowledge. Actual research papers into nuclear reactors and their economic viability can be difficult to find, and the information within must be studied well and analysed within the context of this paper. Indeed, setting the information from the studies into context is one of the challenges with writing about nuclear reactors. Especially considering that, although highly standardized by design, their cost structures can vary by a wide margin, depending on who is buying them, where they are built and how long they take to construct.

These same aspects apply to MSR technology which are not yet commercially available. Sources which state facts about MSR technology had to be analysed and scrutinized and put into context. Many opinions on the subject exist, hence the available research papers which analysed their price structures according to earlier data, helped clear some of the misconceptions about the technology.

1.4 Limitations

Due to the fact that no MSR's are currently in use commercially, it is difficult to find accurate information on the economic viability of these reactor designs. Although they are in development and even in test phase in some countries, this data is difficult to acquire. Furthermore, the amount of different designs currently being pursued makes it difficult to generally discuss their value, be it their economic impact, safety standards or sustainability. A broad look can be, and should be taken, however, this makes comparing MSR technology to legacy reactors somewhat complicated since they both function on similar technology, have non-proliferation issues and cause nuclear waste. Much information on the subject exists, thus in the spirit of keeping this paper relatively short, the aim is to present ideas clearly and in a concise manner so that the reader can easily grasp the concept of this thesis.

2 History of nuclear power

With the advent of the detonation of the very first wartime nuclear weapons made by man during World War II in 1945, the world stepped into the Atomic Age which led to significant changes in both socio-political thinking and technological development regarding energy generation and warfare. Indeed, the two bombs dropped on the Japanese Empire caused such a shift in political thinking that it brought the world to the brink of nuclear holocaust (Weeks, 2011). However, as civilian uses for nuclear power mainly for the generation of electricity were devised, much research and investment into the area of atomic energy production was completed in order to advance our knowledge on the subject. In the end, the Atomic Age became synonymous for its over-glorification of the scope of nuclear energy and forever instilled in the mind a fear for destruction of our world.

The 1950's and 1960's was highlighted by a drive to hype-up the benefits of nuclear energy. Driven by misunderstanding, much of the thought process regarding nuclear power surrounded a vision of the future where everything would be nuclear powered: from cars, to airplanes to homes. Especially in the United States where much of the progress was initially conceived, there was a general feeling that in the future massive nuclear power plants would generate so much energy that it would become "too cheap to meter" (World Nuclear Association, 2014). There was even talk of nuclear powered interstellar travel.

It was during this time that a team of nuclear physicists led by a man named Alvin Weinberg worked at the Oak Ridge National Laboratory to develop nuclear power for both civilian and military use. The work he and his team performed there can be considered as the birth of nuclear power generation - all basic designs for nuclear reactors have their roots within this time and place. Furthermore, the work highlighted the use of multiple methods of electricity generation through nuclear means, including the use of uranium and thorium in different coolants such as water, liquid metal and molten salt mixtures to an extent. Consequently, Alvin Weinberg can be considered as the forefather of both the modern uranium nuclear reactors and the Molten Salt Reactor technology (MSR), which he tested for a period of around five years before the project was cancelled due to political and economic reasons. This project was called the Molten-Salt Reactor

Experiment of 1954 (World Nuclear Association, 2015). In fact, Alvin Weinberg built a nuclear reactor for a bomber airplane with the strategic intent of being capable of flying for long periods of time, which utilized liquid fuel. However, this project was cancelled as well due to issues of viability. Regardless of these setbacks, the value of the work that the team performed at the Oak Ridge National Laboratory cannot be measured considering its contribution to our society today.

The 1970's was highlighted by a decline in the demand for nuclear power due to several factors, key of which was The Three Mile Island accident, where a reactor in the U.S. suffered a partial meltdown due to operator error. This accident did not help alleviate the negative attention nuclear power was acquiring for itself by then. However, it should be mentioned that the oil crisis of 1973 increased the construction and adaptation of nuclear power in other regions such as France (Palfreman, 2014). In 1986 the Chernobyl Accident in Ukraine once again alerted the world to the dangers of nuclear power and ever after since, the nuclear dream that began in the 1950's, peaked around the early 1970's, began a steady and unyielding decline. Since then, nothing as remarkable as splitting the atom has occurred in the field of nuclear energy. At least not beyond the basics that were developed in the first 30 years.

2.1 Present situation

After the hassles of the 1950's and 1960's the world turned its attention to peaceful purposes of nuclear fission. Currently there are over 435 commercial nuclear power stations operating in 31 countries with over 375,000 MWe of total capacity. In 2012, out of the worldwide electricity production total of 22,752 TWh, nuclear reactors provide the world 11% of its electricity demand with reliable and continuous power which is both safe and carbon free due to strict safety regulations, upgraded designs and lack of use of fossil fuels. Furthermore, around 56 countries operate a total of 240 research reactors which provide the world with important radioactive isotopes for use in industry and the medical field (World Nuclear Association, 2016). Civil nuclear power boasts an impressive 16,000 reactors years of experience which is a reflection of the desire to utilize and invest in nuclear energy throughout the years. Although there have been a few notable errors, nuclear power is once again gaining momentum due to various factors such as awareness of the inherent risks involved with coal and gas use in association to the warming of the planet's atmosphere. Furthermore, there are around 180 nuclear plants powering

140 ships and submarines which are in civil and military use. In contrast, only eight countries in the world are known or speculated to have nuclear weapons capabilities, which further validates the preference of civil uses of nuclear energy over militarily ambitions comparatively speaking.

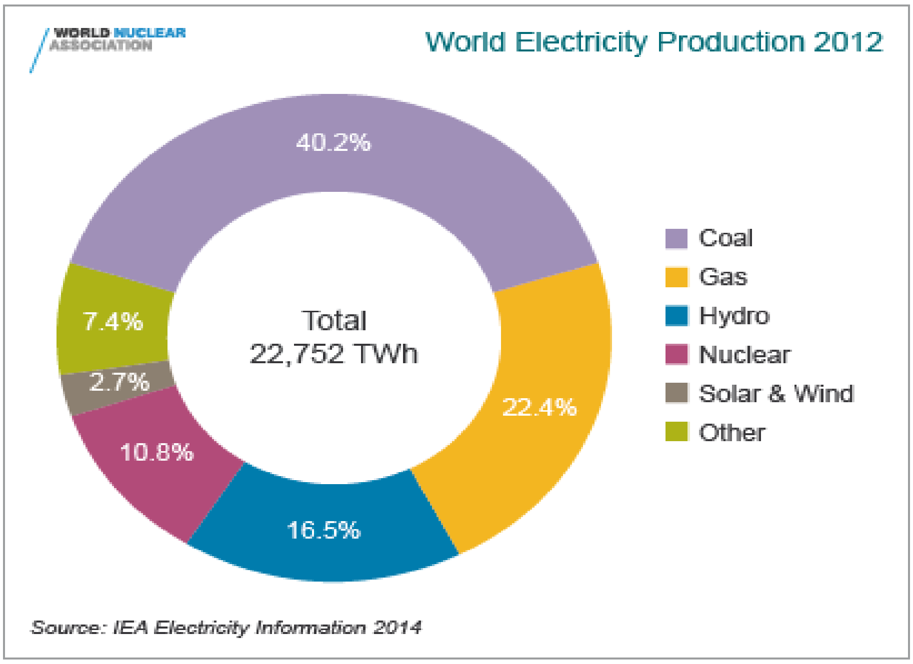


Figure 1. Although nuclear energy has been around for a long time, it still only accounts for 10.8% of world electricity production in 2012 (World Nuclear Association, 2016).

Overall throughout the world, sixteen countries are highly dependent on nuclear power for their energy needs. Nations such as Belgium, Czech Republic, Finland, Hungary, Slovakia and Switzerland get one-third of their energy needs from nuclear energy while France on the other hand acquires three-quarters of its power through nuclear fission (World Nuclear Association, 2016). Historically France has been an advocate of nuclear energy and has contributed to the nuclear community both in research and funding, which might explain the country's infatuation with nuclear energy. Indeed, it is one of the five countries along with China, the U.S., UK and Russia to have signed the Nuclear Non-Proliferation Treaty (NPT) (NTI, 2015). In retrospect, China which has the largest population on earth, currently utilizes only a small fraction of nuclear power for its energy needs; most energy being generated by the use of coal and gas. However, China has big plans for the future where it aims to generate a capacity of 58 GWe, up from the 19 GWe in 2014, with an additional 30 GWe under construction by 2020 (Ong, 2010). The

United States on the other hand acquires only one-fifth of its electricity needs from nuclear power, with little interest in building new reactors. The U.S. is instead concentrating on improving the efficiency of current reactors. Indeed, out of the worldwide 435 reactors, 61 commercially operating reactors are in use in the U.S., whereas compared to China which has 23 active reactors.

3 How nuclear energy works

Currently, most of the world's nuclear power plants in commercial use are Light Water Reactors (LWR) while only a handful are Heavy Water Reactors called CANDU reactors which all utilize 'thermal neutrons' (Nave, 2015). Thermal neutrons are neutrons that have been cooled down by a medium such as water or helium gas to the surrounding liquids temperature. This is important, because it plays a key role in the quantity of isotopes created within the reactor. Nuclear reactors generate electricity through a process called nuclear fission, where a small amount of the original radioactive isotopes' mass is converted into energy i.e. heat as it undergoes fission (Karam, 2006). Uranium, which exists naturally in the world, is an excellent material for generating power. Unprocessed uranium mainly consists of 99,3% Uranium-238 which is not readily fissionable and 0,7% of Uranium-235 which is highly fissionable. Due to the lack of U-235 by mass, this specific isotope is intentionally turned into a powder-like substance called yellowcake, enriched through the use of centrifuges for use in nuclear reactors in order to achieve criticality (Cole & Orlando, 2015).

By enriching the U-235 to around 2,5-5%, it is possible to initiate further nuclear fission within LWR's by causing the U-238 to transmute firstly into U-239, then rapidly into Neptunium-239 and then eventually into Plutonium-239, which by itself is also fissionable and can be used to make nuclear weapons. Eventually when the U-235 burns back down to 0,3% the fuel is in essence spent and must be changed. However, due to the type of undergone fission, the fuel rods retain harmful and very dangerous radioactive isotopes such as americium, technetium, iodine and plutonium (Katusa, 2012). Furthermore, the fuel rods within the reactor are quite inefficient due to the low total consumption of uranium, only around 3% by mass, due to the build-up of xenon and krypton gasses released during fission which can hamper neutron absorption (Lam, 2013). Thus, the fuel rods need to be changed before all uranium can be efficiently used. These elements are some of the major set-backs of nuclear power as the waste generated is harmful up to 10,000 years, thus must be stored with great care and can lead to issues of nuclear proliferation.

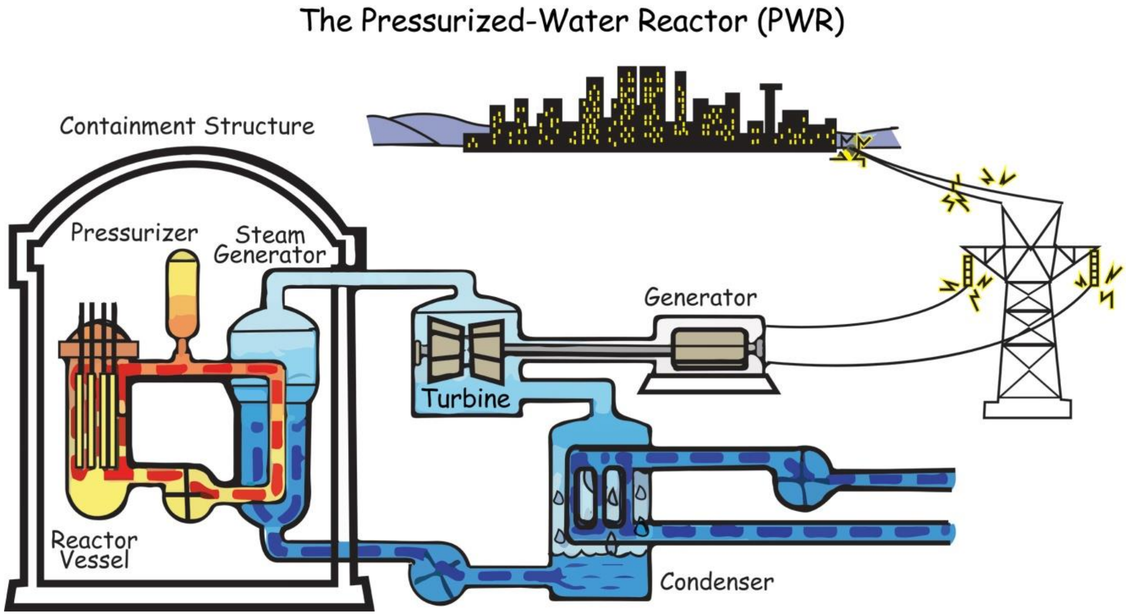


Figure 2. Modern nuclear reactors function by heating water under pressure until it turns to steam. This steam can be transferred to turbines which generate electricity (Energy, 2014).

In essence, the process of achieving nuclear power is akin to throwing a bucket of neutrons at other isotopes in the hopes of creating new isotopes, which in the process of transmutation creates heat via fission. This heat is then captured and used to turn turbines which in turn create electricity. Ironically, one of the greatest achievements of mankind i.e., splitting the atom, equates to little more than a very large and fancy steam engine under peaceful purposes. Although nuclear power provides a large portion of energy via steam, it is still nothing compared to the raw power of splitting an atom, however, humans currently have no meaningful way of utilizing this power directly.

3.1 Light Water and Fast-Breeder Reactors

The amount of U-235 which needs to be enriched for use in nuclear power depends on the intent: LWR's only require low-enriched uranium due to the fact that the process of fission is designed to burn up most of the plutonium which naturally occurs when U-238 captures a neutron within the reactor which in fact constitutes to over one-third of the energy produced. However, fast-breeder reactors, which can be used to make more fuel than is present via breeding, use 15-30% enriched uranium and are intentionally designed to produce more plutonium. Breeding occurs when U-238 isotopes which are more prone to capture fast moving neutrons, captures a neutron and eventually transmutes to a plutonium-239 isotope, thus more U-238 isotopes are converted to plutonium than in LWR systems. Over 30% more fuel can be generated via breeding in some reactors (Karam, 2006).

Although breeder type reactors might seem like an ideal way of generating power due to their ability to create extra fuel, issues of nuclear proliferation arise due to the excess amount of plutonium. This is due to the fact that plutonium, mostly a man-made substance, is an excellent material for nuclear weapons and can be extracted from the core with relative ease. It only takes around 10kg of pure Pu-239 to begin production of nuclear weapons. Subsequently, it takes an enrichment process of over 90% of U-235 for weapons use which makes plutonium a preferred substance (Nave, 2015). Throughout history, only a handful of countries such as the UK, China, US and France have intentionally run many dual projects; generating power for peaceful purposes while generating materials for nuclear weapons. Thankfully, most of these projects have closed down, and those existing are being directed to peaceful scientific purposes. Nevertheless, the issues of nuclear proliferation still exist today, where countries such as Iran and North Korea are subjects of much scrutiny due to their perceived nuclear ambitions and the threat of these weapons ending up in the hands of terrorists (World Nuclear Association, 2016).

3.2 Nuclear fuel cycle

The nuclear fuel cycle is the process of turning raw Uranium-238 into a substance called uranium dioxide (UO2) which can be used as a fuel in nuclear reactors. It is a progressive, step-by-step process which is comprised of the front end and back end phases.

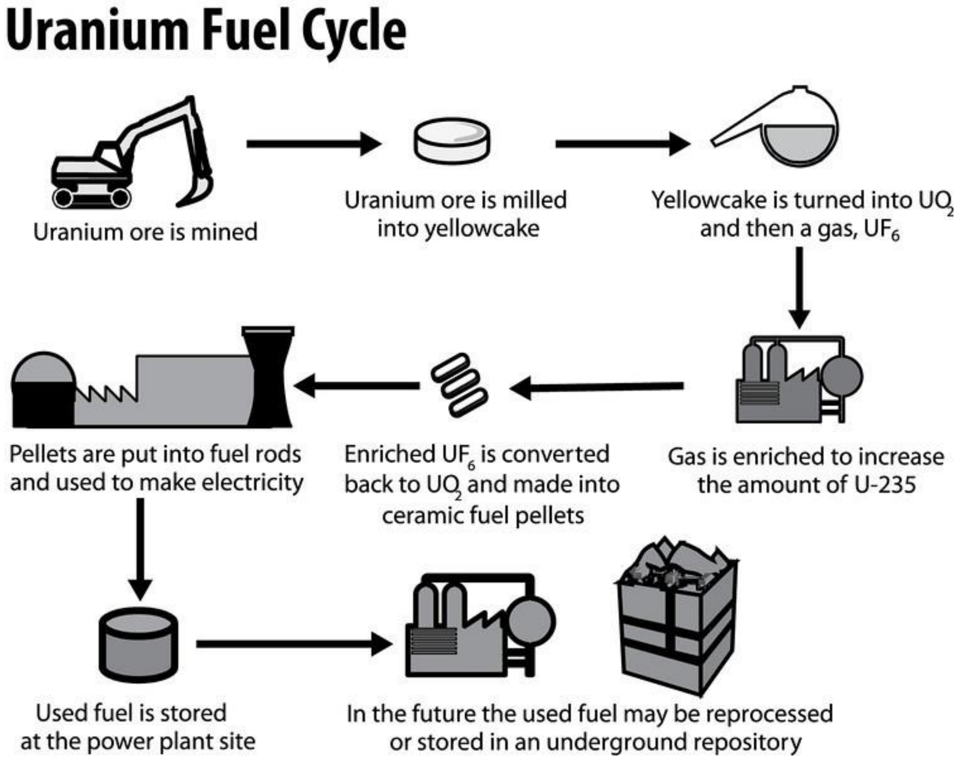


Figure 3. The uranium fuel cycle consists of many complicated phases before the ore can be used as fuel for a nuclear reactor (Cole & Orlando, 2015).

3.2.1 Front end steps

The process of extracting uranium for power generation begins with the exploration of uranium by the use of several techniques: radiometric surveys, chemical sampling of underground water and soils, and exploratory drilling. Once uranium pockets are found, the site is further studied to gauge whether it is economically viable to extract from that source. If the source proves to be economically recoverable, access to the uranium can be done via underground or open-pit mining, or by using in-place (in-situ) solution mining called ‘heap leaching’ that uses liquid solvents to dissolve and extract the uranium from the ore (EIA, 2015).

After the uranium ore is successfully recovered, it is refined into a concentrate at a uranium mill. The uranium ore is crushed, pulverized and ground into a fine powder that is then combined with other chemicals to separate the uranium from the other minerals which are bound within the ore. The final product of this process is a bright yellow substance called U3O8 or ‘yellowcake’ (Cole & Orlando, 2015).

The U3O8 is further processed and converted into uranium hexafluoride (UF6) gas at a converter facility. This process is necessary due to the fact that naturally occurring uranium has three forms or isotopes, U-234. U-235 and U-238, out of which there needs to be a higher concentration of U-235 for optimal efficiency. When UF6 is originally made, the structure of the substance has yet to be altered. This process happens at a uranium enrichment plant where the isotopes within the UF6 are separated. There are various ways by which this separation is possible including gaseous diffusion and gas centrifuge process. In the first process, U-235 atoms are diffused out of the UF6 by the use of a diffuser then collected and concentrated. The final product called enriched UF6 has a concentration of around 4-5% of U-235, which is then sealed in containers and allowed to cool and solidify before transportation to a nuclear reactor fuel assembly. The second process of enrichment is based on spinning the UF6 at extreme speeds in a series of cylinders which separate U-235 and U-238 atoms out of the UF6 due to differences in atomic mass. Modern technologies such as Atomic vapour laser isotope separation (AVLIS) and molecular laser isotope separation (MLIS) use lasers to separate the two isotopes and can achieve much higher material throughput rates (EIA, 2015).

Before fabrication of fuel assemblies can begin, the enriched UF6 has to undergo one final step in order to be used as fuel in nuclear reactors. The UF6 is taken to a nuclear fuel fabrication plant where the enriched UF6 is reacted to form a black uranium dioxide powder. This powder is then compressed to form a small ceramic fuel called a ‘pellet’. Multiple pellets are stacked and sealed within long metal tubes which become the fuel rods used inside the core of nuclear reactors. Multiple rods are bundled together to form an assembly. Depending on the type of reactor in use, an assembly can potentially have anywhere from 179 to 264 fuel rods and a reactor can contain as a many as 121 to 193 fuel assemblies (EIA, 2015). In use, about one third of these assemblies are typically changed out and replaced around every 18 months due to a drop in efficiency caused by parasitic isotopes which are produced during fission within the fuel rods (Nuclear Power, 2012).

3.2.2 Back end steps

Spent fuel from the reactor core is highly radioactive and hot due to the type of elements which have been produced during fission within the core. The spent fuel continues to decay, thus these fuel rods must be stored under water and allowed to cool down for later transportation. These water pools offer a dual purpose: to cool down the fuel assemblies and block the release of radiation. After the fuel assemblies have cooled down for several years they are usually stored on-sight at the power plant itself, stored in large concrete or steel containers which are air cooled (EIA, 2015). Currently, only Finland and Sweden have plans to build permanent underground storage repositories for nuclear waste (Rosendahl, 2015).

Reprocessing of spent nuclear fuel is another option which is currently being utilized by several nuclear energy nations in Europe, including Russia and Japan while other nations such as the U.S. currently have no reprocessing plans. The main driver for reprocessing spent fuel is to extract around 25-30% more efficiency out of spent fuel, thus closing the fuel cycle. Furthermore, by reprocessing spent fuel, the volume of highly radioactive material can be reduced by a factor of one-fifth, with the added benefit that the reprocessed material becomes less radioactive within a time of around 100 years, after which it falls even more dramatically. However, some nations such as the U.S. consider that reprocessing is not worth the effort due to it not being economically viable. Moreover, reprocessing has further factors which need to be considered: out of the nuclear waste, further reprocessing can be utilized to acquire nuclear materials for nuclear weapons, thus very few nations have access to the technology. Conversely, reprocessing can be used to improve the energy security of nations which may not have clear access to new nuclear fuel due to the fact that spent fuel can be partly reused to generate more power. This is especially critical now that the new 4th generation fast-breeder reactors are being considered, which can use new or spent fuel to generate power (World Nuclear Association, 2015).

4 Economics of nuclear energy

Nuclear power is for the most part very cost competitive with other sources of energy generation. Although location and direct access to low-cost fossil fuels play a large role in determining the final cost of electricity from nuclear sources, it is generally accepted that the economics of nuclear power are outstanding in most cases, especially when external costs such as social, health and environmental costs are added to the mix. An important aspect to remember is that the cost of electricity in general is tied to many factors depending on the country in question, location, type of fuel source and applied legal and governmental factors along with subsidies and possible taxes on carbon emissions.

The following graph shows the total cost in cents from different energy sources utilized in the U.S. As can be seen, nuclear is the second cheapest source of energy, followed by coal and wind. In order to actually calculate these figures, each source must be normalized to their respective capacity factor, adding in the life span and total energy production, such as 0.5 trillion kilowatt hours over an operational period of e.g. 60 years. Each source has its benefits and disadvantages: coal and gas burning facilities are relatively cheap to build but typically become more expensive due to the precarious nature of gas and coal prices. On the other hand, nuclear plants, wind and solar have expensive up-front costs but the longer they operate, the cheaper they become (Conca, 2012). However, it must be noted that since solar and wind are intermittent sources of energy, which means that they must be compensated by other sources of energy since storing of energy efficiently is currently not possible.

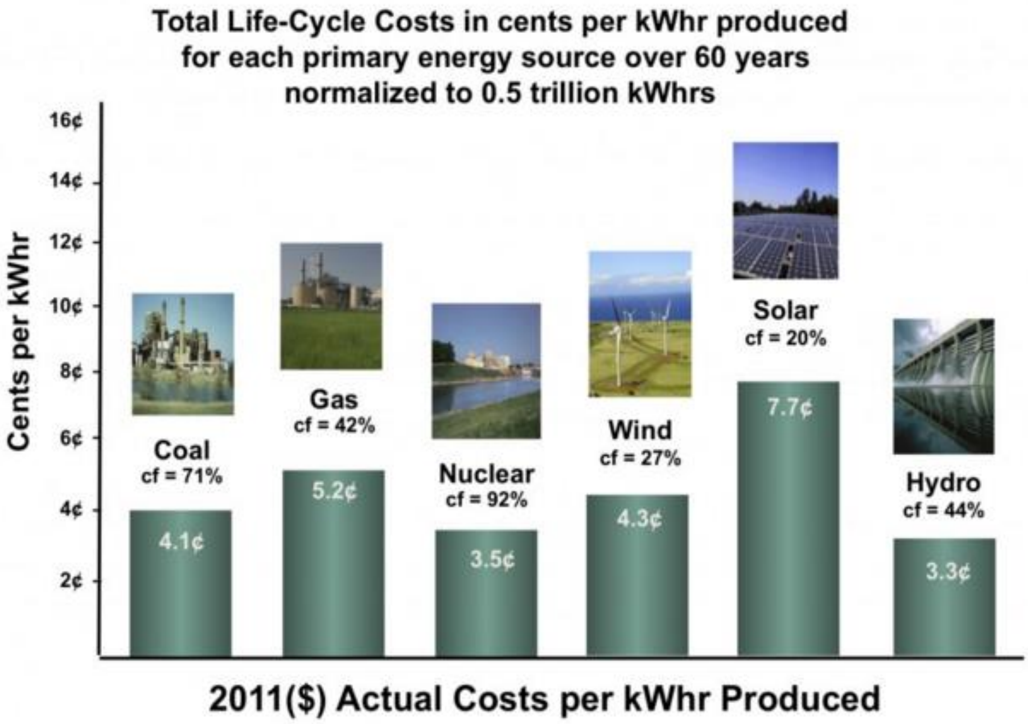


Figure 4. The actual costs per kWh for nuclear power is 3.5 cents ($) with an effective capacity of 92% (Conca, 2012).

In simpler terms, nuclear power plants are expensive to build but relatively cheap to operate thanks to the massive amounts of continuous energy that can be extracted from that source. Some of the costs included in the price are: fuel costs, operations & maintenance costs, production costs and the cost of decommissioning. Unlike alternative renewable sources of energy production, nuclear power can be operated continuously, only having to stop operations when new fuel is added or maintenance is made adding to their value against other sources of energy. Fuel is typically added every 18-24 months which leads them to be less dependent of price volatility compared to gas and oil (Nuclear Energy Institute, 2015). However, capital costs for building a nuclear plant are higher than those of coal-fired or gas-fired plants due to the need for extreme safety standards. Indeed, construction of nuclear power plants is usually undertaken by large companies in tandem with government foresight and sponsoring. The typical build time for a Light Water Reactor (LWR) is around five years however, some projects such as the Olkiluoto 3 reactor project in Finland has taken much longer due to various issues (Schlissel & Biewald, 2008).

Fuel costs for a typical 1,000 MWe Boiling Water Reactor (BWR) or Pressurized Water Reactor (PWR) consist of 30% of overall production costs which equals to around $40 million for one year based on an 18-month refuelling cycle. Comparatively, fuel costs for natural gas, coal and oil consist of 80% of the production costs and are much more prone to price volatility, regardless of whether the effect is positive or negative (Nuclear Energy Institute, 2015).

Upfront capital costs associated with construction are the primary source behind the costs for nuclear power plants. Estimating the final costs of nuclear power plants is extremely difficult due to the many variables which have a direct impact on the final price. Factoring in cost of land, cooling towers, switchyards, interest rates on loans and inflation all impact the final price (Schlissel & Biewald, 2008). Due to this large price tag, nuclear power needs to be financed as an investment, thus needs to be done through interest payments over the life of that loan, which if the project exceeds its estimated completion date, can become a major burden financially. Indeed, due to the fact that nuclear power plants take relatively long to build and are capital intense, the predicted price can easily swell. While a natural gas powered plant could be built for a price of $850/kW, a similar nuclear plant costs $4000/kW to build which translates to a final price tag of around $4 billion. However, due to inflation and the interest on the debt needed for the project, and considering the time it takes to build the plant, the price may inflate up to $17 billion over the lifetime of the project, including eventual interest payments (Schultz, 2012).

The projected operating costs for these plants is around 30 cents per kilowatt-hour (kWh) for the first 13 years until construction costs are paid off, dropping to 18 cents per kWh for the remaining lifetime (Sovacool, 2008). Although the interest payments are typically borne by the government and eventually the tax-payer, since they are the ones to benefit from the power generated, this price is not directly translated to the customer due to subsidies placed on nuclear energy and the fact that the price of electricity is calculated as a lump sum from various sources of power. In the United States e.g., federal subsidies play a major role in the incentives regarding which energy source to invest in. Indeed, some have claimed that nuclear power is only possible due to the generous subsidies that the government gives to nuclear power and considering that the nuclear industry is the third most heavily subsidized industry per-kWh basis in the U.S., this claim could be true. However, nuclear still receives less subsidy than that of solar and wind. Regardless of source, these subsidies inherently alter the cost structure and competitiveness, making their price estimation difficult (Schultz, 2012).

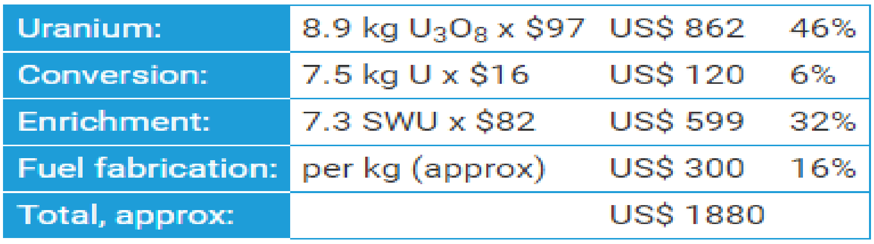
4.1 Factors affecting the price of nuclear power

Nuclear power plants are expensive to build, and along with this issue they suffer from factors which greatly affect their price. Petrochemicals and other energy production sources such as coal and natural gas require commodities, resources, and manufacturing capacity which usually overlap with those of nuclear projects, which makes the overall global competition for these goods and services quite fierce. This can lead to cost overruns, and due to the high demand of key commodities such as steel, copper and concrete can result in double-digit annual increases of these goods. The nuclear energy industry also suffers from a limited number of manufacturers and suppliers that can produce these goods which can lead to bottlenecks in production if there are multiple orders simultaneously. Currently there are only two companies in the world that have heavy-forging capabilities for nuclear power plants: Japan Steel Works and Creusot Forge in France (Schlissel & Biewald, 2008).

Due to the adaptation of other sources of power, a significant drop in suppliers of nuclear power components has occurred in the last two decades. In the US, there are currently fewer than 80 suppliers with the required nuclear N-stamp which allows the manufacture of components for nuclear purposes. This means that there is a much larger overall reliance on overseas manufacturing for systems and components which will invariably affect the price due to transportation and commissioning costs. Furthermore, these components need to be inspected for quality which takes time and further resources. The lack of suppliers and firms willing to undertake construction means that there are fewer bidders for work which can lead to higher prices. Moreover, the investment scenario has changed throughout the years, where earlier payment schedules and longer delivery times are to be expected. Long lead times in the pre-production phase of six to seven years can be expected for key plant components. In addition, the demand and cost for both on-site construction labour and skilled manufacturing labour has increased (Schlissel & Biewald, 2008).

For the foreseeable future, there seems to be little reprieve for the high demand due to the limited number of suppliers. Although a set price is given, historical evidence suggests that cost over-runs are common within the nuclear construction industry. Adding to this, many construction companies are unwilling to commit to fixed price contracts with fixed schedules. They target recovery of actual costs, including overruns, and wish for a high return. This leads to the owners and customers having to deal with the whole sum of the overruns (Schlissel & Biewald, 2008). Furthermore, newer plants may face unexpected increases in costs due to the dependency on operational learning, the competitive nature of the industry in parallel with rapidly changing technology such as with the Olkiluoto plant in Finland, changing liberalized market conditions and public opinion. Moreover, due to the fact that the market is in a state of flux due to new designs and increased demand for cleaner energy, standardization is difficult which means no mass production of units, thus economies of scale are hard to achieve. Historically speaking, in the U.S. which has been the world leader in nuclear technology, 75 of the existing plants exceeded industry quoted costs by more than 300%. These costs were $45.2 billion in 1990 but ended up costing $144 billion when extrapolated to the same time frame. The increase was from $938 per installed kW to $2,959 per installed kW. History shows us that building nuclear plants is expensive with a high risk of overruns (Sovacool, 2008).

Table 1. Reprocessing price break-down of uranium to usable fuel. At 45,000 megawatt day per tonne burn-up, 360,000 kWh of electrical power per kg can be achieved. With these figures, the fuel cost is 0,52 c/kWh (World Nuclear Association, 2015).

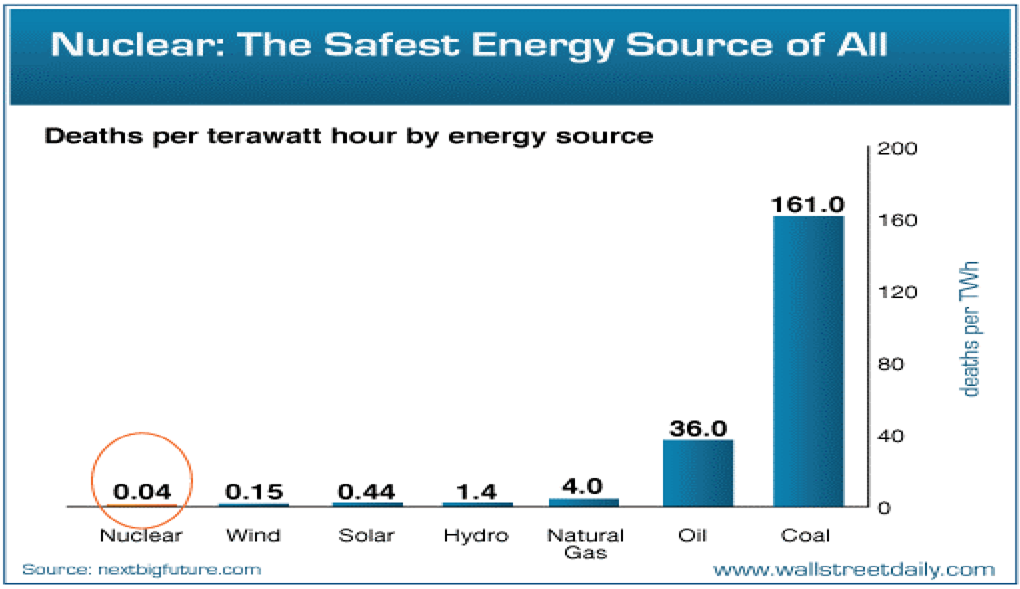


Uranium:	8.9 kg U_3O_8 x $97	US$ 862	46%
Conversion:	7.5 kg U x $16	US$ 120	6%
Enrichment:	7.3 SWU x $82	US$ 599	32%
Fuel fabrication:	per kg (approx)	US$ 300	16%
Total, approx:		US$ 1880	

Aside from the construction costs, the price of the uranium fuel needs to be considered as well. In general, fuel costs for nuclear power are lower compared to coal, oil and gas-fired plants. According to the U.S. Nuclear Energy Institute, 78% of the price of these plant derives from fuel costs. For gas-fired plants, the figure is around 89% and for nuclear plants this cost is around 14% (World Nuclear Association, 2016). Moreover, raw uranium as it exists in nature, needs to be reprocessed much further than e.g. coal or oil before use thus increasing its associated cost. However, since much more energy can be extracted out of a smaller quantity of uranium than other sources, this gives nuclear energy an advantage over other sources. The above table shows the price break-down of reprocessing for 1kg of uranium as UO_2 reactor fuel at current long-term prices.

4.2 Advantages of nuclear power

With all the costs and dangers associated with building nuclear plants, it should be noted that nuclear energy alongside with coal and gas, for all their pit-falls, are the backbone of modern civilization. Without them, mankind would not have reached as far as it has without them. Indeed, one of the greatest advantages that nuclear power provides is not only in its capability to efficiently deliver continuous power around the clock, but it is also able to do it by producing energy with almost zero greenhouse gasses (GHG's) compared to coal and gas. According to a study by NASA in 2013, nuclear power, ever since its inception, has prevented the loss of life of around 1.8 million people over a 30-year period due to the fact that nuclear power does not dump GHG's into the atmosphere. Nuclear energy ranks last in deaths per energy unit produced, even when taking into account past accidents; coal and gas are silent killers, while nuclear has a very public profile (Kurzgesagt, 2015). The public is very much aware of events such as the Chernobyl accident in 1986 and the Fukushima-Daiichi accident in 2011 which leads to a distorted view of the facts regarding nuclear energy, whereas many neglect to take into account that coal and gas alone kill hundreds of thousands of people yearly on average (Merchant, 2013).

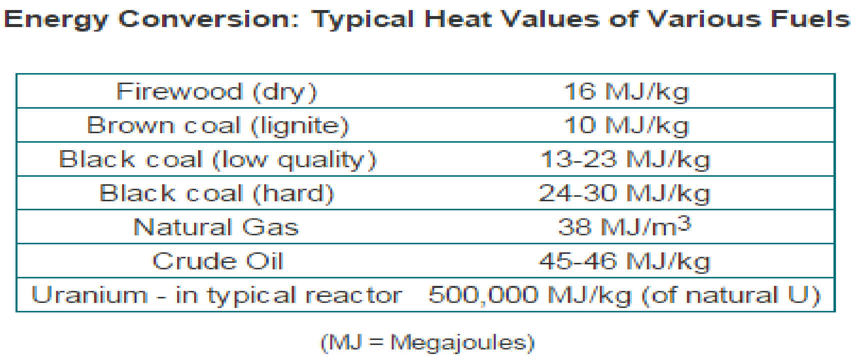


Deaths per terrawatt

Figure 5. Nuclear power causes the least deaths per TW/h produced, whereas Coal with its in-direct impact causes the most (Militello, 2014).

Moreover, the negligible amount of GHG's that nuclear power produces, which is mostly through in-direct factors such as transporting of fuel during mining and shipping, and other externalities, translate directly into less GHG's into the atmosphere comparatively which means there is less impact on the climate and the heating of the atmosphere. On the other hand, nuclear waste is a severe ever-present issue which needs better options for future storing. However, its presence does not have a similar impact on nature and humans when safely stored, unlike coal and gas emissions which have a costly, direct impact.

Table 2. By far, Uranium has the best energy conversion rate when compared to other sources such as coal and oil (World Nuclear Association, 2012).



Energy Conversion: Typical Heat Values of Various Fuels

Firewood (dry)	16 MJ/kg
Brown coal (lignite)	10 MJ/kg
Black coal (low quality)	13-23 MJ/kg
Black coal (hard)	24-30 MJ/kg
Natural Gas	38 MJ/m^3
Crude Oil	45-46 MJ/kg
Uranium - in typical reactor	500,000 MJ/kg (of natural U)

(MJ = Megajoules)

Nuclear energy also has very low operating and fuel costs compared to other forms of energy production. The estimated lifetime of a nuclear reactor is around 40-60 years, depending on how, and how often it is used (Brooks, 2015). Moreover, the more a nuclear power plant is used, the greater the decrease in price is for the customer. The greatest advantage of nuclear energy is its capability to produce massive amounts of energy from a single, relatively small source. Indeed, the energy density of the uranium used in nuclear reactors is so great, it far surpasses any other form of energy production, thus is the primary reason why nuclear power is economically viable. In order to generate the same amount of power as a 10 gigawatt (GW) nuclear plant, which occupies an area of 2km^2, renewable energies such as wind and solar require an area of 5000km^2 and an area of 400km^2 respectively. This does not even begin to take into account the manufacturing, assembly and maintenance costs. Moreover, since these sources are intermittent, their average capacity factors are estimates to be at 25% for wind and 20% for solar, compared to that of nuclear power which is at 90% (Banerjee, 2014). Table 2 above exemplifies the energy potential from various sources. As can be seen, the potential for energy generation from nuclear power far exceeds any other source.

5 New design frontier – Molten Salt Reactors (MSR)

Current designs for nuclear reactors have not changed much since the 70's, due to a variety of reasons such as R&D costs and incentives, huge up-front costs and the basic fact that current nuclear reactors are relatively easy to build and maintain. The technology is tried and true and due to their robustness, leaves little incentive to invest in new types of reactors, especially since the cost of extracting electricity from other sources of power is highly competitive compared to that of nuclear power. However, the Fukushima-Daiichi accident in 2011 led to changes in mindset by both the public, mostly in a negative manner, and the engineering community which sees the benefits of continuing with nuclear power.

Many new designs for nuclear reactors have been introduced in the past. However, the process of screening, regulating and accepting these designs takes a long time, especially since there is no governing over-arching body which oversees such actions. Currently, a coalition of 13 countries including the US, China, France, Japan, the UK and the EU (Euratom), which are part of 'The Generation IV International Forum' (GIF) have banded together to research and develop the feasibility and viability of future nuclear reactors, namely six different 'fourth generation reactors'. These reactors are based on various designs and have the intended purpose of being sustainable, economically viable, safe, reliable and proliferation-resistant (World Nuclear Association, 2015). The estimated target of deployment is between 2020-2030, and considering that the project for these designs began in 2000, simply shows how long it can take for new designs to be implemented. Currently, six billion dollars is being invested in these technologies over a lifetime of 15 years, where 80% of the costs is being met by the USA, Japan and France. Out of the six new designs, most have closed fuel cycle designs to maximize the resource base and minimize high-level waste, which needs to be dealt with after use. Three of the designs include fast neutron reactors (FNR).

5.1 Advantages and disadvantages of MSR’s

The importance of this technology lies in its research into new ways by which to minimize the risk and maximize energy output. As stated before, current designs are based on using water or helium as a coolant. Regarding its effectiveness as neutron decelerator, water is an excellent medium due to its molecular composition. However, the risk of a catastrophic meltdown due to high pressure which needs to be continuously cooled can result in an explosion which typically ejects radioactive water and steam into the atmosphere and surrounding area. Hence, the development of Molten Salt Reactors (MSR) has once again spurred internationally, especially after the Fukushima-Daiichi accident.

MSR's by design are as old as Light Water Reactors (LWR) but they utilize a special salt-mixture as a coolant instead of water or helium in the form of molten fluoride or chloride salts. This special mixture acts both as the coolant and medium of heat transfer, and is much more efficient at it than water due to a much higher heat threshold and lower pressure. This idea had already been invented and tested during the 1950's at the Oak Ridge National Laboratory though the concept did not gain as much attention due to political and economic reasons (World Nuclear Association, 2015).

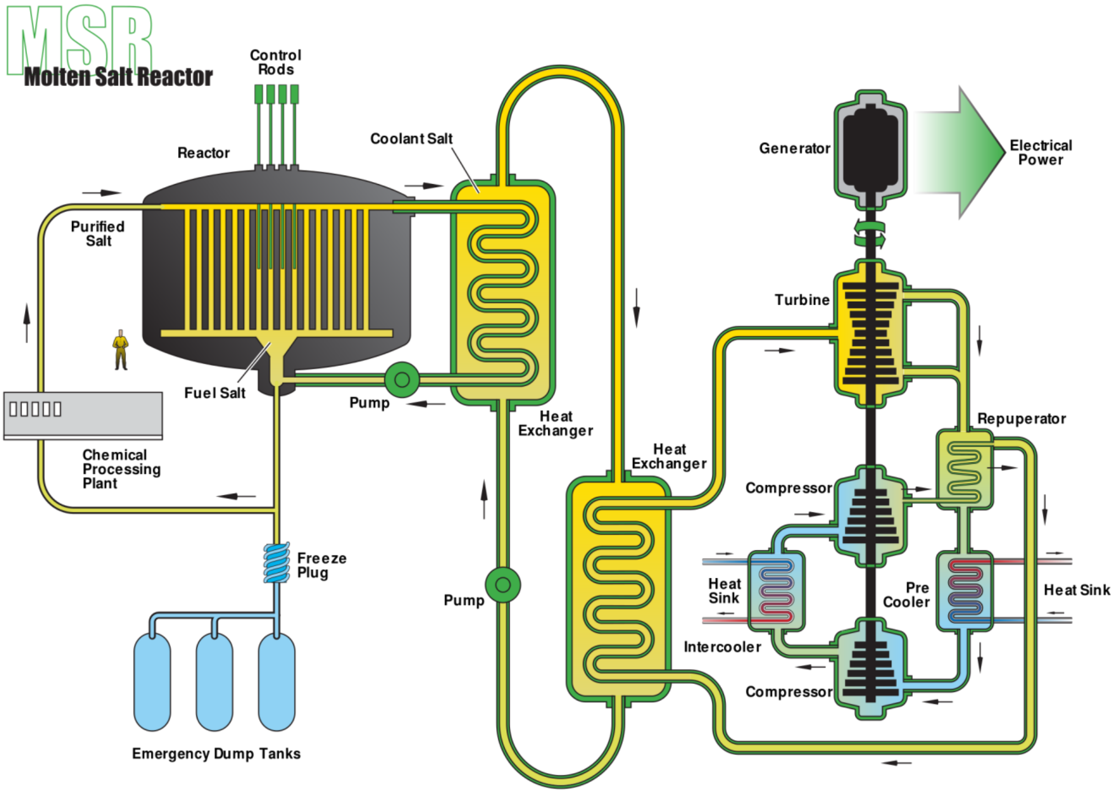


Figure 6. Instead of using water and steam, MSR technology is based on circulating molten salt mixtures throughout different loops in order to transfer heat into the turbines for electricity generation. This heat can be used for other purposes as well (Touran, 2015).

The greatest aspect of the MSR is that the liquid salt which is heated up to 700^{0}C acts as the coolant and medium for transfer of heat which remains liquid at 500^{0}C without pressurization and up to 1400^{0}C although this has not been extensively tested yet. In contrast PWR's operate at 315^{0}C under 150 atmospheres of pressure. The importance here is that that the heat produced by an MSR is much more effective at producing electricity and can be utilized in tandem to desalinize water and potentially create petrol and radioactive isotopes for medical use (Flibe Energy, 2016). This process is simply not possible with modern reactors due to the use of water as a coolant; the water itself is not hot enough for viable use and the hydrogen produced by the pressurized water is dangerous which is one of the main caveats of modern nuclear reactors (Buxbaum, 2011). This gives MSR based technologies a huge advantage over older designs.

Currently there are many types of concepts for MSR's, where the uranium fuel is either in solid state as in Light Water Reactors or dissolved into the salt coolant itself, although this process is further from commercial development than solid fuels (World Nuclear Association, 2016). The liquid mainly consists of lithium and beryllium fluoride (FLiBe) salt with dissolved low-enriched uranium (U-235 or U-233) fluorides (UF^4) mixture for fission i.e. heat generation, and stable criticality is assured through the use of control rods for neutron absorption.

Aside from being extremely safe due to the fact that MSR's cannot technically explode due to the lack of hydrogen because no water exists in the system, they are also more efficient at producing energy and produce less waste due to better burn-up. The molten salt mixture itself allows for parasitic neutron-absorbing gasses such as xenon to fizzle out of the salt, which leads to better neutron absorption, which in turn allows for greater efficiency (World Nuclear Association, 2015). Subsequently, more fuel is being used which leads to less waste. Furthermore, in uranium fuel-salt mixtures, a case can be made for proliferation-resistance due to the salt fuel within the core being extremely cross-contaminated with non-weapon specific isotopes such as uranium and plutonium, making their separation a lengthy and expensive process (Flagg, 2015). However, the ingenuity of those determined to acquire these isotopes for nuclear weapons should never be underestimated thus once again highlighting the danger behind the improper use of nuclear technology.

MSR's also incorporate several other safety designs which are both cheaper and simpler than in modern nuclear reactors. A freeze plug situated at the bottom of the container where the core is as seen in Figure 8, is cooled by a fan and can be made to unfreeze if an accident were to occur. This would cause the salt-fuel to simply drain into a passively cooled emergency dump-tank below thanks to gravity, and since the salt-fuel is no longer heated, the salt itself would begin to cool down and solidify. Issues of further criticality are dealt with through the design of the dump-tank which is highly neutron aborting, i.e. has poor qualities for good neutronics (Jorgensen, 2015). However, current new designs for MSR's utilize the concept of solid fuels with salt coolants, where issues of criticality are handled through the use of control rods which absorb neutrons and stop fission from occurring. In contrast, if the salt-fuel beings to overheat, MSR's are designed to passively regulate their own temperature: this occurs because the reactivity in the core automatically slows down due to thermal expansion i.e., it becomes harder for the isotopes to fission due to the increased distance from one another, which in turn leads to a cooling down of the liquid. Indeed, the use of salts within MSR designs has a dual use, both of which are beneficial, making them much safer than legacy reactors.

5.2 Assumed costs and other factors

Although the fourth-generation of nuclear reactors are on their way, their actual price of construction, investment and the effect on the price of electricity are difficult to estimate, especially since so many variables are in effect. These costs are one of the issues which these reactors are trying to address. MSR technology presents a few key factors which lower the up-front costs by huge margins. Due to the fact that the coolant is in a partially molten format, MSR's are by design cheaper to build than conventional nuclear reactors - the necessity for large cooling towers is completely forgone thus the need for expensive pressure valves and specialized piping systems is severely limited. Although cooling systems within MSR's exist, they are much smaller and easier to build. This also means that they have a much smaller physical footprint which leads directly to less up-front costs. Some have even speculated that due to their small size and ease of construction, MSR's could technically be built in factories and shipped on to location instead of building on site which is expensive and time consuming (Jorgensen, 2015).

Despite the fact that the guideline on building MSR's has been around for quite some time, MSR designs have gained little attention for a long time due to cheaper alternatives.

The research is lacking and it is done by small groups. Investment is relatively low as well and can be hard to come by. The technology itself suffers from a few notable caveats such as which salts to use: there are multiple different types of salts with different chemical compositions for several differing reactors designs. The effectiveness of these salts still needs to be studied, especially considering the fact that the salts themselves can be corrosive and may damage the container which holds the core (World Nuclear Association, 2015). Not all salts have this issues, such as FLiBe, however, this particular salt mixture is expensive and quite problematic to manufacture due to the extent of the needed purity of the mixture (Halper, 2013). Moreover, some new MSR designs create issues of nuclear proliferation because in some instances extracting weapons-grade material such as uranium-233 becomes easier.

6 Thorium – The forgotten substance

It is difficult to estimate which new reactor design(s), if any, will become the mainstream reactors in the future just as LWR's did back in the day. However, there is a new frontier of reactors which is once again considering using breeding without the hassle of producing weapons-grade plutonium in excess. These reactors utilize a material called thorium (Th) and they show a lot of promise regarding clean and safe energy generation.

Discovered in 1828 by Swedish chemist Jakob Berzelius and named after Thor, the Norse god of thunder, thorium is a slightly radioactive chemical element with the atomic number 90. It is one of the three primordial elements still in existence along with uranium and bismuth. In nature, thorium is mainly present in its single isotopic form Th-232 due to its half-life of over 14 billion years which makes it a highly stable element. Thorium can be found in igneous rocks and is plentiful in sands, due to its insolubility, but more often in the rare-earth phosphate Monazite. Thorium is also a typical by-product of rare-earth mining (Thorium, 2011). Moreover, it is three to four times more abundant than uranium in nature which makes it much easier and cheaper to acquire. Currently, large stockpiles exist: the world total of stored thorium is estimated to be around 6,355,000 tons (World Nuclear Association, 2015).

Regarding the of future MSR technology, thorium can be used in conjunction with current uranium reserves to compliment future overall fuel stockpiles for energy generation through breeding. This is due to the fact that thorium, although fertile, can be made to fission when exposed to neutrons. Similar to U-238, which eventually becomes Pu-239, thorium transmutes to uranium-233 when exposed to neutrons thus becomes an excellent fissile fuel material. In addition, thorium (Th-232) has a better absorption rate of neutrons than uranium, nearly three times that of uranium, thus allowing for a higher conversion to U-233 than U-238 to Pu-239. Due to these characteristics, thorium is a good material for breeding - its neutron release, i.e. 'conversion ratio' is higher than 1.0, which means the fuel is self-sustaining (World Nuclear Association, 2015). This U-233 can then be used 'in-situ', i.e. within the core of an MSR to generate more fission, or can be chemically separated from the mix for use as new fuel or for the production of nuclear weapons, depending on the design of the MSR. The important factor to remember is that thorium, as a fertile material, always requires a fissile 'driver' material such as uranium or plutonium in order to fission. One of the great advantages of using thorium in MSR reactors is that there is an added safety feature - remove the driver and the fission stops. Moreover, thorium reactors can be used to reduce stockpiles of weapons-grade plutonium because this material can be used as the driver for fuel within the reactor core.

Waste from thorium based reactors such as Liquid Fluoride Thorium Reactors (LFTR) is much lower due to the conversion rate of thorium into usable fuel. 98.5% of the thorium itself is used up in the process of energy generation which means there is much less waste left over before new fuel is added compared to the use of uranium fuel rods (Thorium, 2015). In fact, modern uranium burners are highly inefficient compared to that of thorium. The thorium dioxide used in LFTR's is chemically more stable than uranium dioxide, which allows for greater fuel efficiency. Furthermore, due to the characteristics of thorium, it has higher energy production per metric ton - an estimated 1 ton of thorium can produce as much energy as 200 tons of uranium and 3,5 million tons of coal due to its ability to fission so well (Kurzgesagt, 2015). In addition, uranium-238 is only one single neutron absorption away from producing the first transuranic isotope Pu-239, while thorium based applications are five neutron absorptions away from producing the first transuranic isotope. This in essence means that less harmful long-lived waste such as Neptunium, Americium and Curium are produced in the core of a liquid fluoride thorium reactor, although it does occur and are part of the braw-backs of the technology.

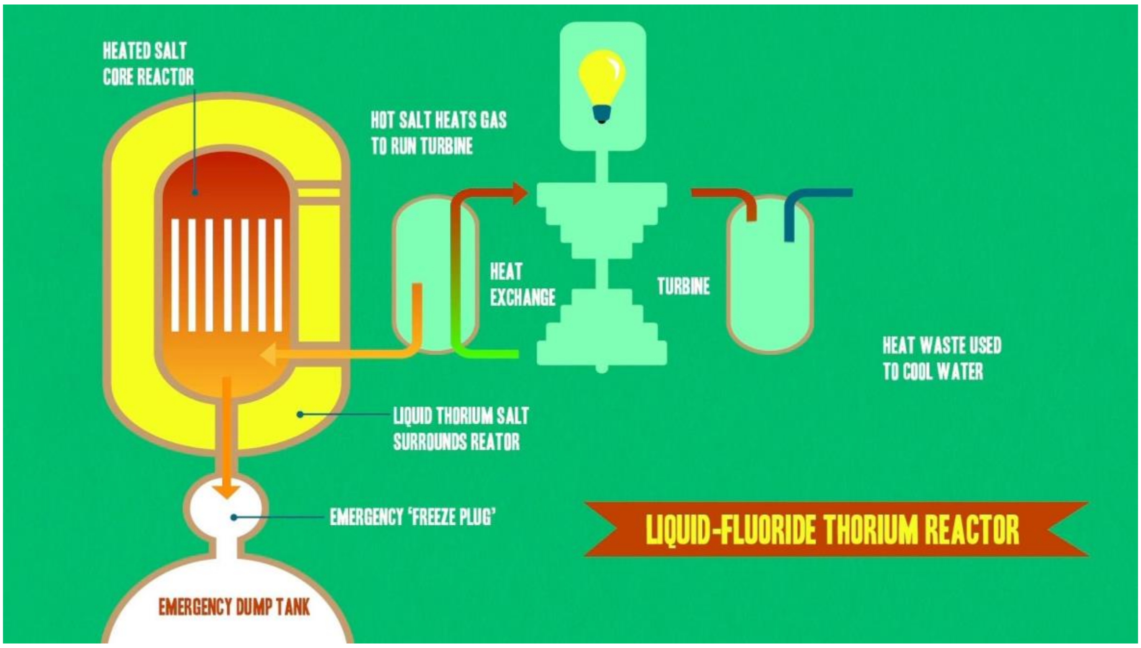


Figure 7. This particular LFTR uses a dual salt mixture: one which acts as a blanket or 'driver' at the core, and another which uses a mix of thorium fuel for breeding (Green, 2012).

Nuclear Proliferation is of great concern when it comes to any nuclear reactors. LFTR's in general have better proliferation-resistant characteristics than that of uranium reactors. Whether used in a single-or-dual loop MSR system, the U-233 produced in the reactor is unclean and chemically contaminated with U-232 which is a strong gamma-ray emitter. These gamma-rays are hard to contain, unless within the core of a reactor, which means producing weapons out of the material is not only dangerous for the people involved, it also has a high chance of destroying the electric circuitry within the weaponry. Moreover, these gamma-rays are much easier to detect thus, it would be economically more viable to enrich uranium-235 or acquire plutonium by other means (Lerner, 2012).

However, the technology is not without its draw-backs. As with any MSR related technology, the salt mixture needed for cooling the fuel can be expensive to produce which will increase costs. These costs are offset by the smaller footprint of the reactor building, but must still be taken into account. Furthermore, the thorium dioxide is expensive to make due to its high melting point of 3,350^{0}C, requiring much higher sintering temperatures to produce high density $Th0_2$. The $Th0_2$ is as well relatively inert, which means the salt mixture must contain the right portion of acids to dilute the substance. This means that there is a higher risk of corrosion to the equipment and piping. However, this can be negated by using additional aluminium nitrate, but is highly dependent on the type of design and fuel used and may add additional costs. The conversion chain of Th-232 to U-233 is also slightly problematic. Protactinium-233 is produced as an intermediary through the fission process of Th-232 to U-233, and has a relatively long half-life (~27 days), thus requiring a longer cooling time of at least a year which affects the cost of storing the spent fuel. In addition to having relatively long-lived isotopes within, the waste from the thorium cycle leaves behind strong gamma-ray emitting daughter products such as Bismuth-212 and Thallium-208 which have half-lives of around 73.6 years. As a result, greater care must be taken when dealing with the fuel cycle of thorium, however, there are less dangerous materials produced and they have shorter half-lives compared to legacy reactors (IAEA, 2005).

6.1 Development and factors of cost

Due to the fact that no commercially operated LFTR's are yet in existence, it is difficult to estimate the total costs that an undertaking to build an LFTR would cost. However, there are various small private companies which are very eager to research and promote their designs of MSR's such as Transatomic, FLiBe energy and Lightbridge corporation. These companies are at the forefront of the technology but face issues regarding regulation and investment. Indeed, investment into MSR technology is picking up slowly due to the lack of standardization of the new technology. Research, which takes many years to acquire, is hard to come by thus investors are unwilling to commit to a technology which might become obsolete in a short period of time due to issues of opportunity cost (Thorium, 2011). However, the cost saving factors that MSR technology features, such as the necessity for less building materials through a smaller footprint, potential for mass production, easy maintenance and the added safety features are all positive attributes of the technology and encourage more research and investment.

Transatomic, a spinoff group from MIT, designed a new reactor which could theoretically produce 20 times more power than earlier similar designs. It would be small-scale, yet reliable and safe. It could be factory built which would save up on the costs of building the plant. It would include the basic safety feature of basic MSR designs as well. The estimated cost would be $1.7 billion for a 500-megawatt power plant which is much lower than legacy reactors of the same capacity. Regarding these legacy reactors, they generate 20 metric tons of high-level waste a year which can stays radioactive for 10,000 years, while this new design is expected to produce 250kg of waste which stays hazardous for only a few hundred years (Bullis, 2013).

According to Transatomic, their designed plant could be fuelled by nuclear waste such as plutonium which would aid in nuclear non-proliferation efforts by reducing stock piles of weapons (Bullis, 2013). Another report states that the capital costs for a 1 GW thorium power reactor could be as low as $780 million. Moreover, the operation and maintenance of the reactor is estimated to require less staff, which would drop the cost estimates for personnel expenses from $50 million to $5 million. In addition, waste disposal costs could be as low as $1 million or less per year due to high burn up efficiency of thorium compared to uranium. The cost estimate for electricity from these designs is thought to be as low as $1.4c/kWh (Zou & Barnett, 2014). However, other sources place the price to be at around 3,8c/kWh (Moir, 2001).

Regardless of the direct price of electricity to the consumer and their current development costs, what is important is the question of how competitive MSR technology is compared to other sources of power? Many nations still embrace coal & gas as their main sources of power generation however, considering how unclean and damaging these sources of power are, there is significant interest in developing technologies which are cleaner and sustainable, including nuclear power and renewable energies such as solar and wind. These developments will always shape the overall price of electricity in any given nation thus the final price is difficult to assess. Considering the future development of energy needs, the world energy demand is expected to increase by 56% by the year 2040, regardless of source (EIA, 2013). Developing nations such as China and India, with their huge populations are pushing hard to respond to growing demand and are developing and investing in new sources of energy generation. For China, with pollution problems, MSR reactors present a valuable option for them regarding energy generation. Indeed, China has invested large sums of money in developing Molten Salt Reactors (Touran, 2016) (Zou & Barnett, 2014). Meanwhile, India is also looking to complement its energy generation via investing in the use of thorium to compensate for its lack of uranium stockpiles (Prabhu, 2015).

7 Sustainability and future outlook

In the future, the demand for electricity is anticipated to increase as the population of the earth grows from 6.7 billion in 2011 to 8.7 billion by 2035. Overall population growth, urbanization and increased standards of living in developing nations will put pressure on the demand for energy. Indeed, electricity demand has increased twice as fast as overall energy use and is expected to rise more than two-thirds from 2011 to 2035, where over 70% of the increase is coming from developing nations such as India and China. Moreover, the UN Population Division estimates that the process of urbanization will continue where it was 52% in 2011, and is expected to reach 62% in 2035. By 2050 this figure is expected to be at 70% which should enable the population of the world to stabilize to around 9 billion people (World Nuclear Association, 2015).

Organizations such as the OECD's International Energy Agency (IEA) have laid out several key scenarios which attempt to estimate the future demand of electricity for this growing population by a few margins. Stated in their *World Energy Outlook 2013* report, the estimated demand for electricity from the year 2011 to 2035 is expected to be 81% (19,004 TWh to 34,454 TWh) under their *Current Policies* scenario and slightly lower at 69% (32,150 TWh) in their *New Policies* scenario. Once again, the most drastic demand will come from the developing nations; in Asia, the average projected growth is calculated to be 4.0% or 3.6% per year respectively until 2035. However, considering the bigger picture, there is little difference in the end sum as the real question lies in which sources of energy are going to be used to generate that power (World Nuclear Association, 2015). Furthermore, even though the population of the earth is expected to rise, at present there are around two billion people who have little or no access to electricity which is an indicator that even at current generational capacity, not all people are covered. This clearly indicates that overall demand could be much higher if everyone had unhindered access to electricity.

7.1 Future estimates for energy sources

Currently, most global demand for electricity is generated via two sources: burning coal which in 2012 was around 40.2% of the world electricity production and 22.4% gas respectively. This means that over 60% of the world's demand for energy comes from direct carbon emitting sources. Both of the sources are expected to increase in demand in the future. Demand for coal and gas is expected to grow 0.7% and 1.6% annually respectively from 2011 to 2035. However, the electricity production shares from these two source is expected to change: although both will see a rise in overall demand, the use of coal for electricity will increase by 35% by 2035 yet will relinquish its current 41% status down to 33%, eclipsed by other sources such as a massive increase in gas use by 72% by 2035. Although this increase in gas use may seem as a large step, considering the amount of electricity needed in the future, gas is expected to retain its original 22% share of the world electricity production, where other sources such as renewable sources play a much larger role. Renewable sources and hydropower are expected to increase nearly by five-fold by 2035. However, they would still only account for a small portion of the total energy production. According to the *New Policies* scenario, Nuclear power on the other hand is also expected to retain its smaller share of 12%, growing 66% per annum (World Nuclear Association, 2015).

7.2 Energy security and the nuclear approach

Although nuclear power only makes up a small portion of the global energy mix, it is nonetheless a very important source of energy for maintaining the base-load of energy demand throughout a twenty-four-hour cycle. Indeed, in most cases nuclear energy is utilized as a constant source of reliable power to maintain the power-grid. With the exception of e.g. France, where nuclear power is used for the vast majority of electricity production due political and economic reasons, most countries that utilize nuclear energy only produce a moderate amount of electricity through nuclear power, which maintains the base-load of the grid (Nuttall, 2007). It has been argued that legacy based nuclear power plants cannot cope with the peaks and troughs in energy demand which occur throughout the day and to an extend this is true depending on the design. Power stations which are designed to upkeep the base-load include coal power stations, hydrothermal and geothermal stations. Conversely, gas, solar, wind and diesel are peak load stations (SinoVoltaics, 2015). However, modern and 4th generation nuclear plants have been designed to operate at full capacity at all time if need be (World Nuclear Association, 2014).

7.2.1 Drivers which increase the demand of nuclear power

As the global population is expected to grow, especially in the developing nations, more and more people will need access to both clean water and stable electricity. This increased demand will drive all nations to either increase and/or renew their sources of power for their energy mix. Currently, in the U.S. and EU the goal is to diversify and renew existing capacity to meet demand, while in the developing nations the agenda is to have enough capacity to supply their growing economies (World Nuclear Association, 2016). Although demand for nuclear energy does not currently seem to be on the agenda within the developing nations, with the focus on renewable sources, nuclear energy does play a key role in maintaining the base-load of the grid and is a valuable alternative for coal and gas to an extent due to its much lower carbon-footprint.

Furthermore, other sources such as the increased use of electric cars and water scarcity are further driving the need for more electricity. Currently, over 783 million people do not have access to clean and safe water, out of which 37% live in Sub-Saharan Africa and this number is expected to grow in the future as less sources will be available (WHO, 2012). An analysis done by the International Food Policy Research Institute (IFPRI) found that 4.8 billion people and approximately half of global gain production will be at risk due to water stress by 2050 if no changes are made. While around $63 trillion or 45% of total GDP will be at risk due to water stress by that same year (Growing Blue, 2016). Hence, water scarcity will not only become a major issue for those that do not have access to clean water but will also become a major factor in limiting growth for the global economy.

Moreover, the sales of electric vehicles are expected to rise dramatically in the future. Led by increases in oil prices and broader market access to cheaper electric vehicles due to improvements in the technology (McDonnell, 2016). This will increase the electricity demand on the base-load generation as most recharging will happen during the night-time. The expected night-time use could increase as much as 50-70% of the total (World Nuclear Association, 2015). This draw will have to be compensated by an increased use of coal, gas or nuclear power. However, when considering the technological advancements that MSR technology has, these new reactors could potentially have an answer for both of the above problems. Molten Salt Reactors are designed to be more efficient than legacy reactors while also being safer. They can also be used to desalinate water in conjunction with generating power. This means that if nuclear power is to be used to compensate for the increased demand in electricity, MSR's should seriously be considered as they serve a dual purpose (McGinnis, 2012).

Concerning climate change, many developed nations have vowed to at least try to reach a carbon-neutral economy by the end the mid-century. This move is driven by increased awareness of the dangers that fossil fuels pose for the warming of the planet. The risks that sea level rise pose on coastal areas and the effects on the average increase in global temperature can have on the planet are the main causes of concern. As such, fossil fuels need to be replaced by low-emission source of energy, such as nuclear power and renewable sources, which happens to be readily available. Indeed, on a global scale current nuclear power use actually reduces the carbon dioxide emission around 2.5 billion tons per year relative to if the same amount of energy was produced by coal-fired plants (World Nuclear Association, 2015).

Geopolitical factors play a key role in energy security as well. Uninterrupted supply of energy, whether it comes in the form of coal, gas or oil has to be maintained, however, historically this has not always been possible as witnessed e.g. in the Oil Crisis of 1973 (World Nuclear Association, 2014). Although very little oil is used to produce electricity worldwide, primarily used for transportation, price shocks generated by such events illustrate the vulnerability of nations to fluctuations in supply. Interruptions in delivery of gas such as what Russia has done to Ukraine pending payment in 2015, has caused energy disruptions throughout country (Shankar, 2015). In this regard, nuclear power is at less risk to interruptions as uranium is a relatively common ore, 500 times more common than gold, found in rocks and seawater. Large concentrations of uranium are not that uncommon either, which implies that supply of the material is not limited to a few regions (World Nuclear Association, 2015). However, uranium is susceptible to price fluctuations just as coal, oil and gas but due to the fuel cycle of nuclear reactors which is around 18-36 months, this means that within that timeframe, there is no need for constant supply of that fuel. Compared to coal or gas which requires a constant supply of new fuel, nuclear energy has much less inherent risk of interrupted delivery which means it is less prone to geopolitical tampering. Furthermore, the cost of the fuel is mostly included in the lifetime cost of the plant due to the huge upfront costs. Reprocessing of nuclear waste for energy can also be used to mitigate the effects of energy insecurity. Therefore, delivery of fuel and price are minor risk factors for nuclear energy (World Nuclear Association, 2015).

Currently, mining of uranium ore is limited to a few key regions such as parts of Africa, North America and Russia. However, production is expected to increase as demand increases (World Nuclear Association, 2015). Currently there are only a handful of uranium suppliers, mostly concentrated in Europe, the U.S. and Russia due to the access to large enrichment plants. Historically these nations held a cartel position on the material, where access to the fuel was made through direct contracts with the supplier and buyer as uranium is not a commonly traded commodity. Although the market for uranium has eased, it is still a supervised commodity.

Lastly, there is much debate over the cost-effectiveness of nuclear power. Several studies have shown that in the long-run, nuclear energy is more cost-effective than other sources such as coal, gas or even solar and wind. Although nuclear power has extremely high upfront costs, maintenance, personnel and associated fuel cost are only a small part of the operational lifetime cost of the plant, which can extend from 40 to 60 years. Moreover, nuclear energy has the potential to generate large amounts of continuous electricity at low prices, whereas similar capacities from other sources cannot economically be obtained due to the limitation of the capabilities of the sources. For instance, when one ton of natural uranium is utilized, some 44 million kilowatt-hours of electricity can be produced. If the same amount of production would be applied to fossil fuels such as coal or gas, some 20,000 tons of black coal or 8.5 million cubic meters of gas are required respectively (World Nuclear Association, 2015).

Considering that demand for electricity is going to increase as the population, urbanization and the economies of developing nations grow, there is going to be more demand for energy generation. This demand is likely going to increase the price of fossil fuels in the long-run unless they are compensated by more production. However, when the focus is on cutting back emission, introducing carbon reduction plans and curbing subsidies for the fossil fuel industry, this is going to further increase the price of fossil fuels in general and potentially highlight the benefits of nuclear power even further. Moreover, improvements in the designs of nuclear reactors such as Molten Salt Reactors (MSR) which have the specific goal of decreasing the upfront cost of building these plants while at the same time making them safer and more efficient, is predicted to increase the demand of nuclear power compared to fossil fuels (Banerjee, 2014).

7.3 Rapid deployment of nuclear energy

In the future it is possible that more nuclear power is adopted as a part of the energy mix at a much faster pace. According to the Nuclear Energy Agency (NEA) (2014), the average time to build a nuclear power plant is expected to take around 5-7 years. However, this estimate does not take into account the time required for planning and licensing. The shortest build times have been noted in nations such as South Korea and China with 4-6 years possibly due to better access to materials and financing. In Europe, the construction time ranges from 6-8 years. Comparatively, large coal plants and natural gas fired plants can be built within 4 and 3 years respectively. The average cost of building for 3rd generation reactors, operating at 1400-1800 MWe, in OECD countries is around $5-6 billion (NEA, 2014).

However, funding and investment for nuclear power projects will need to be made easier and an incentive has to be created by dropping subsidies to fossil fuels which in 2009 was around 312 billion mostly in non-OECD countries. Currently, the focus has been on investing and utilizing cheap dirty fuel which has created a trade-off between energy security and the acquisition of cheap energy (World Nuclear Association, 2015). If there is no change in direction, a possible supply crisis situation will be created, where dirty and expensive energy will be and continue to be the catalyst of increased extreme weather phenomenon which will impact the lives of billions of humans. Nuclear power, on the other hand, can reduce the dependency on outside sources for energy and curb CO2 emissions in a cost effective manner.

Even after the evident decline of nuclear power which began in the 70’s, 218 nuclear power plants around the world started operating in the 1980’s, which was on average of one every 17 days. The average power of these plants was 923.5 MWe. Out of the 218 operational reactors, 47 were in the U.S., 42 in France and 18 in Japan (World Nuclear Association, 2015). This pace declined in the later years, however, it is still a testament to the speed at which these types of plants can be built under the right incentives. Indeed, considering the speed at which China and India need to modernize their energy mix in order to supply their economies and populations with energy, the process of investing and building new nuclear power plants is expected to hasten.

Currently, over 60 power reactors are being constructed around the world in 15 different countries. Notable targets for nuclear power are China, South Korea, the UAE and Russia. The New Policies scenario in the World Energy Outlook 2014 states that, out of the expected 10,700 GWe total in 2040, nuclear capacity will grow by 60% through 543 GW/e in 2030 to 624 GWe in 2040, where 46% of the growth in capacity will be centred in China followed by a lump-sum of 30% for India, South Korea and Russia combined (World Nuclear Association, 2016). This goes to show just how heavily China is invested in the developed of nuclear energy - for economic and energy security reasons. Plans show that China currently has 22 plants under construction with plans to build more. China's goal is to achieve energy production of 58 GWe by 2021 and up to 150 GWe by 2030 (World Nuclear Association, 2016).

Taking this information into account and considering that the demand for energy has doubled since the 1980's to 2015, if the course for nuclear energy would be synergized with the build-up of the 1980's, it is a realistic estimate that the equivalent of one 1000 MWe power plant could be started-up every five days worldwide (World Nuclear Association, 2015). However, as stated previously in this paper several factors such as access to cheap sources of fossil fuels, legislation, public opinion, and the scarcity of suppliers for key components is withholding demand for nuclear power. Therefore, the capacity to acquire more energy from nuclear power seems to be in place but the willingness is not there yet.

8 Conclusion

Nuclear power has been around for a long time and it is ironic, consider that fact, that only after a catastrophic event such as the Fukushima-Daiichi disaster and the increasing impact of climate change, that we are now starting to look for better alternatives than those of fossil-fuels. These fuels have been our greatest ally in allowing us to develop quickly in a relatively short period of time. However, at the same time, their abundance and easy access have created a situation which is unsustainable in the long run. Indeed, the compiling problems caused by climate change will force us to take action whether we are ready for it or not. Thus, it is now time to embrace new methods of power generation so that future societies and our descendants can prosper without compromise.

However, this choice is not going to be easy. Our lives are intertwined with the access to abundant and cheap fuels which means breaking away from them is going to be a difficult, if not impossible, choice without extreme changes to current mindsets. This is especially apparent considering how dependent the global economy is on cheap fuel. Nuclear power is a viable option but is by no means the easiest to implement, as their implementation is highly dependent on various factors such as economics, geopolitics and access to cheaper alternatives. As such, nations are typically highly limited regarding the type of power they have access to: some nations have greater access to cheap energy while others are at a greater mercy of market fluctuations and geopolitical events. Energy infrastructure projects are extremely expensive as well and take many years to develop.

Developing nations with large populations such as India and China are pushing ahead with the development of new nuclear technologies out of necessity. The U.S. on the other hand is content with refurbishing their current fleet of nuclear reactors and relying on other sources such as natural gas while Europe is in a state of flux: some are investing in renewable technology while most are content to acquiring their bulk energy needs from countries such as Russia in the form of natural gas. However, due to geopolitical shifts and market fluctuations, no country is completely safe regardless of their energy mix, especially when taking into account the goals for sustainability. Considering the advantages of MSR designs, many countries could eventually invest in them due to their added safety and sustainability features while also mitigating the effects of energy dependence.

Indeed, this change should be undertaken preferably sooner than later; currently no other sources of energy exist yet which are capable of replacing coal, gas and nuclear as base-load providers. Although much can be achieved through the use of renewable technology, due to their function as peak-load providers and intermittent nature, they are mostly capable of providing only a fraction of the needed energy. Even though many nations are investing in renewable technologies, the cost competitiveness of the technology compared to other sources must be considered as well. The question of sustainability is also a question of price; not all nations can or should adopt the energy mix of other nations.

Considering the approach towards sustainability that must be undertaken due to the negative factors caused by fossil fuels and the limits of renewable technology, it seems that nuclear energy is currently the only way forward if the sustainability goals that have been set are to be achieved. However, pushing forward with outdated designs should not be the way to go. Considering the fact that Molten Salt Reactors by design are a superior choice compared to legacy type reactors, they should become the principal choice of reactor once the technology matures. However, MSR's still need to prove their effectiveness and in order for this to happen, wider adaptation of the technology is required along with further research, investment and an open mindset. Only time will tell at what pace this will occur, but taking a look at the speed at which e.g. China is forced to adapt new energy technologies in order to combat environmental issues and pressures of urbanisation, the adaptation of these new design could occur relatively fast.

Finally, nuclear energy is definitely not meant for every nation nor should it completely overtake the energy market of a nation. A healthy energy mix based on low-carbon emitting sources such as nuclear and renewable technologies should be adopted in order to reach a carbon-neutral economy in the future, leading to a cleaner and more prosperous world.

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