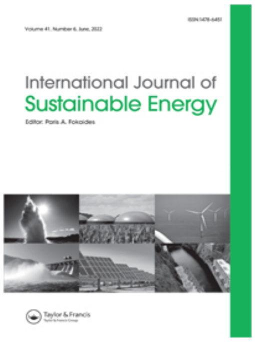

International Journal of Sustainable Energy

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/gsol20

Safe, clean, proliferation resistant and cost-effective Thorium-based Molten Salt Reactors for sustainable development

Jan Emblemsvåg

To cite this article: Jan Emblemsvåg (2022) Safe, clean, proliferation resistant and cost-effective Thorium-based Molten Salt Reactors for sustainable development, International Journal of Sustainable Energy, 41:6, 514-537, DOI: 10.1080/14786451.2021.1928130

To link to this article: https://doi.org/10.1080/14786451.2021.1928130

INTERNATIONAL JOURNAL OF SUSTAINABLE ENERGY
2022, VOL. 41, NO. 6, 514–537
https://doi.org/10.1080/14786451.2021.1928130

Taylor & Francis
Taylor & Francis Group

Safe, clean, proliferation resistant and cost-effective Thorium-based Molten Salt Reactors for sustainable development

Jan Emblemsvåg

NTNU Ålesund, Ålesund, Norway

ABSTRACT

Sustainable development requires sustainable energy sources. Nuclear energy is proposed, but it is perceived as problematic in terms of proliferation, waste, safety and costs. In this paper, these issues are analyzed, and it is demonstrated that this perception is not rooted in the reality of modern nuclear technologies. In fact, the paper concludes that Thorium-based Molten Salt Reactors (TMSR) technology is clean, safe, proliferation resistant and cost effective, and even better than traditional nuclear technologies. Given that thorium is a plentiful resource, this technology can propel humanity forward for the next 1000 years or more. What is lacking is an understanding of TMSR by those who allocate funding for research. Hence, this paper is also a call for action.

ARTICLE HISTORY
Received 2 February 2021
Accepted 5 May 2021

KEYWORDS
Levelized Cost of Energy; Light Water Reactors; Monte Carlo simulations; renewable energy; uncertainty analysis

1. Introduction

Energy is one of the driving forces in socio-economic development (Olsson 1994). Sustainable development must be predicated on a sustainable energy system. To that end, nuclear energy is recognised as a key technology in reducing carbon emissions (IPCC 2014), which is based on studies reporting that the same amount of electric energy may be produced from three million tonnes of coal, from U-235 extracted from about 200 tonnes of natural uranium, or from merely one tonne of the plentiful natural resource, thorium (Rubbia 2016).

Despite improvements in reactors, ‘nuclear power faces stagnation and decline’, as the interdisciplinary study on ‘The Future of Nuclear Energy’ report states (MIT 2003; 2009). Notably, the Molten Salt Reactor (MSR) is not mentioned, and even textbooks on nuclear engineering have excluded MSRs since the late 1970s (Furukawa et al. 2008). MSRs are discussed in an updated revision of the aforementioned report (MIT 2018), which highlights four critical problems that must be overcome for nuclear power acceptance: (1) safety, (2) waste, (3) proliferation and (4) costs. These four issues are the focal points in this paper. Despite some shortcomings, the MIT interdisciplinary studies offer solid assessments, particularly for the Light Water Reactor (LWR) technologies.

This paper demonstrates the potential advantages of the MRS concept, and poses the hypothesis that ‘Thorium-based Molten-Salt Reactors (TMSR) concepts will provide safe, clean, proliferation-resistant and cost-effective energy for sustainable development.’ The TMSR technology is benchmarked against LWR technologies, and both technologies are discussed in

CONTACT Jan Emblemsvåg emblemsvag@yahoo.com

terms of safety, waste management and proliferation issues in Section 2. The analysis shows that LWR is much less problematic than many fear, but MSRs offer more benefits and less risks.

MSR technology also works with uranium – it is only a matter of using the right salt chemistry in the fuel cycle (see World Nuclear Association 2020). This paper discusses the TMSR because it is arguably easier to promote to the public in many countries, and there is no published data on uranium-based MSRs. However, there is little reason to believe uranium fueled MSRs will deviate significantly from the TMSR, and uranium-based MSRs may increase in popularity over time as seawater has abundant uranium, see Section 2.2, thereby potentially eliminating the need for mining.

Due to the relatively little published knowledge about MSRs (Mignacca and Locatelli 2020), Section 2.3 takes a deeper dive into technical issues to discuss safety, waste management, proliferation and overall technical feasibility. This paper follows the approach of integrative literature reviews whose purpose is to create initial and preliminary conceptualizations and theoretical models, rather than review old models. This type of review often requires a more creative collection of data, as the purpose is usually not to cover all articles ever published on the topic but rather to combine perspectives and insights from different fields of research traditions (Snyder 2019).

In Section 3, a comparative cost analysis of these two nuclear technologies is provided using the Levelized Cost of Energy (LCOE) approach to focus on the costs together with basic requirements that concern the public – waste, safety and proliferation. The costs are important because the necessary economic drivers for devoting significant industrial resources to that end are not yet clearly established (OECD/NEA 2015). Furthermore, technology costs are key assumptions to the integrated assessment models (IAM) the IPCC uses when estimating the mitigation pathways going forward (see Rogelj et al. 2018). Hence, nuclear power will play a larger share in the IAM scenarios as it becomes more cost effective. The paper closes in Section 4 with a brief discussion of implications and directions for future research.

2 The nuclear options

As of year-end 2018, the commercial nuclear reactors installed globally were as follows (IAEA 2019):

- 71% are Pressurized Water Reactors (PWRs), which is one of three types of Light-Water Reactors (LWR). This is the type of reactor involved in the 1979 Three Mile Island accident (NRC 2021a).
- 18% are Boiling Water Reactors (BWRs), which is the second of the three types of LWR. The Fukushima Daiichi powerplant used this type of reactors (World Nuclear Association 2021).
- 6% are Pressurized Heavy Water Reactors (PHWR), which use heavy water (deuterium oxide) as moderator. Unlike LWRs, they have separate coolant and moderator circuits (World Nuclear Association 2011).
- 2% are Light Water Graphite Reactor (LWGR), which this is the reactor type involved in the Chernobyl accident in 1986 (World Nuclear Association 2011).
- 2% are Gas Cooled Reactors (GCR) and Advanced Gas-cooled Reactors (AGR) where carbon dioxide is used as the coolant and graphite as the moderator.
- 1% is Fast Breeder[1] Reactor (FBR) types, where the fuel is a mix of oxides of plutonium and uranium but no moderator. This type of reactor was involved in the partial meltdown of the Fermi 1 reactor in 1966 (NRC 2021b).

Nuclear energy has some challenges with public perception due to accidents as noted in the list of options (OECD/NEA 2015). Publicity surrounding these incidents generates concerns regarding safety, waste management and proliferation. The next section will focus on these matters to establish a reference line from which TMSRs can be discussed.

2.1. Nuclear safety, waste management and proliferation issues

The fact is that new LWR plants, properly operated, meet strenuous safety standards (MIT 2003), and a recent estimate presented in Figure 1 shows that nuclear energy is among the safest energy sources. Furthermore, it is estimated that 1100 people die annually due to the phase-outs of the German nuclear power plants (Jarvis, Deschenes, and Jha 2019) due to poorer air quality.

When it comes to proliferation, the historical fact is that only the USA has ever detonated a nuclear device with the intent of harming people. Proliferation must therefore be seen more in the context of the fuel, because the composition of used LWR fuel is approximately 94% uranium, 1% plutonium, and 5% waste products (ORNL 2012). In total, as of 2008, more than 2200 tonnes of plutonium existed throughout the world in the form of spent nuclear fuel, nuclear weapons components, various nuclear inventories, legacy materials, and wastes (LANL 2009). More specifically, the total world generation of reactor-grade plutonium in spent fuel is circa 70 tonnes per year. About 1300 tonnes have been produced so far, and most of the plutonium remains in the used fuel, with some 400 tonnes extracted.[2]Thus, the objective is to minimise the proliferation risks of the nuclear fuel cycle operation (MIT 2003).

Over the decades, much effort has been made to avoid spreading nuclear material with somewhat mixed success. However (MIT 2003), is confident using the 'once-through thermal reactor fuel cycle' approach for any new installations will facilitate an acceptable level of proliferation resistance when combined with strong safeguards and security measures and timely implementation of long-term geological isolation.

It is important to note that so-called nuclear waste is not waste in the traditional sense – often it can be reprocessed and reused at some cost. Depending on regulations and risk preferences, there are two avenues – a closed loop with reprocessing of spent fuel or an open, once through fuel cycle (MIT 2003);

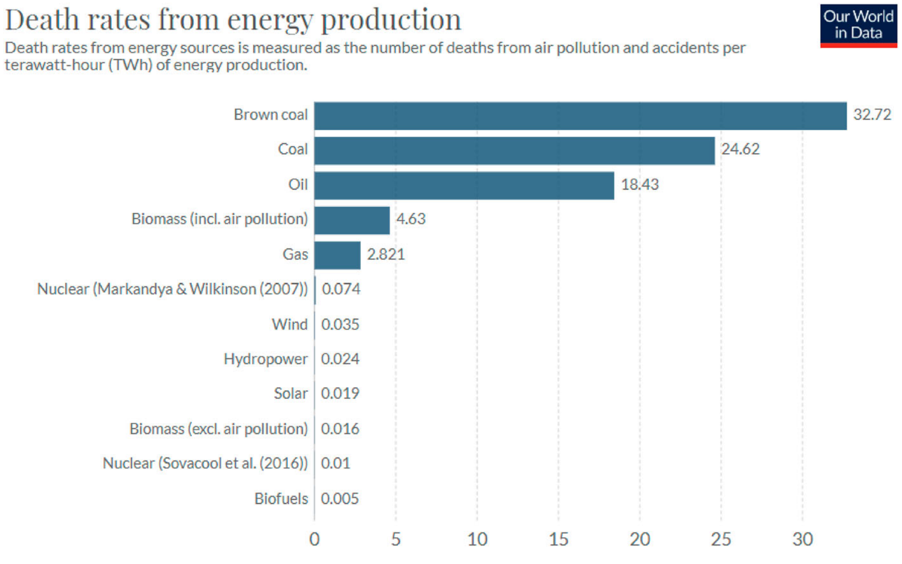

Figure 1. Death rates by energy source. The graph is compiled by Our World in Data using information from (Markandya and Wilkinson 2007) and (Sovacool et al. 2016).

> A convincing case has not been made that the long-term waste management benefits of advanced, closed fuel cycles involving reprocessing of spent fuel are outweighed by the short-term risks and costs. Improvement in the open, once through fuel cycle may offer waste management benefits as large as those claimed for the more expensive closed fuel cycles.

Based on the total projected Red Book[3] resources, 13 million tons are recoverable at a cost less than $130/kg (in 2006 USD), or approximately an 80 year supply for 800 reactors (OECD/NEA and IAEA 2008). Most commentators conclude that a half century of unimpeded growth is possible, especially since resources costing several hundred dollars per kilogram (not included in the Red Book) would also be economically usable (MIT 2009), and an established strategy to store spent fuel for a period of several decades can create additional flexibility in the waste management system. Exploitation of the entire conventional resource base would increase this outlook by about 300 years (OECD/NEA and IAEA 2008), before we take into account the fact that nuclear is renewable, as discussed in Section 2.2, and the fact that modern nuclear technology is far more effective as a source of energy generation. Yet, if only 10% of the projected increase in energy capacity is met by nuclear energy, the current installed capacity would have to more than double with a corresponding impact on uranium requirements (OECD/NEA and IAEA 2008). Using data accounting for almost 95% of all nuclear power reactors in the world, the (IAEA 2018) writes that;

> … there is an estimated 250 000 t HM [Heavy Metal] of spent fuel in storage worldwide and 120 000 t HM of reprocessed spent fuel. The current total global inventory of solid radioactive waste is approximately 35 million m^3, of which 28.5 million m^3 (82% of the total) has been disposed of permanently and a further 6.3 million m^3 (18%) is in storage awaiting final disposal. More than 98% of solid waste is classified as being very low or low level waste in volume terms, with most of the remainder being intermediate level waste. In terms of total radioactivity, the situation is fully reversed, with approximately 98% of the radioactivity being associated with intermediate and high level waste.

This statement means that much of the waste is already handled by systems that have been significantly improved over the last two decades (IAEA 2018), and today's nuclear technologies, which are predominantly LWR, are manageable within strict regulations and with proper execution. However, in light of the nuclear innovations discussed later, nuclear technology is improving and a radically different approach needed. Newsweek described it as a 'lost chance' stating that 'The most promising path forward is to return to the road not taken 50 years ago.'[4]The technology Newsweek refers to is explained in more details in Section 2.3. First, Section 2.2 presents research that supports the hypothesis that nuclear energy is renewable.

2.2. Nuclear energy is renewable

The heading of this section may seem provocative to some, but recent research from geological observations and nuclear simulations suggest that the centre of the earth is a deep geological reactor (Hollenbach and Herndon 2001). Geomagnetic field reversals and changes in intensity are understandable from an energy standpoint as natural consequences of intermittent and/or variable nuclear fission chain reactions deep within the Earth. Furthermore, the production of helium, having ^{3}He/^{4}He ratios within the range observed from deep mantle sources, is demonstrated to be a consequence of nuclear fission. Based on the simulations, researchers estimate that there are vast amount of uranium and thorium (more than a trillion tonnes) deep in the earth nuclear core.

Additional indicators come from studies of seawater which found both uranium and thorium in huge quantities. When it comes to thorium, there are major variations in the estimates (Huh, Moore, and David C. 1989) with concentrations of thorium higher towards the bottom of the oceans (Nozaki and Horibe 1983). However, whether the deep-sea bottom acts as a sink or source is unclear (Huh, Moore, and David 1989). Pore water concentrations are much higher than typical thorium concentrations in seawater (Cochran et al. 1986).

When it comes to uranium, however, the research is more conclusive and researchers estimate that approximately four billion tonnes at a concentration of 3.3 ppb are found in seawater (Tsouris

2017). In addition, uranium is being replenished from the ground, and (Cohen 1983) estimates that by using breeder reactors there is enough uranium on earth for its remaining geological life, and innovations, such as pyroprocessing researched by (ANL 2018), will improve the situation further in the coming years.

Recently, researchers at Pacific Northwest National Laboratory (PNNL) demonstrated that uranium can be washed out from seawater using inexpensive simple yarn (Bauer 2018). Over the last 20 years, uranium spot prices have varied between USD10 and USD120/lb of U_3O_8, mainly resulting from changes in the availability of weapons-grade uranium to blend down to make reactor fuel. Currently, the U_3O_8 extracted from seawater is estimated to cost about USD200/lb (Conca 2016). The costs are expected to fall significantly making nuclear material from seawater economically feasible within a few years. Thus, it has been shown that nuclear energy sources are plentiful and accessible by methods that are both renewable and sustainable.

In the remaining paper, the objective is to demonstrate that TMSRs will make the case for nuclear energy even stronger, and confirm the hypothesis of the paper.

2.3. Introducing the Thorium-based Molten Salt Reactor (TMSR) concept

A Molten Salt Reactor (MSR) is the generic term for a class of fission reactors that use a fluid molten salt mixture as fuel, and operates at low pressure (Allibert et al. 2016). There are many different designs, where some use uranium, Transuranium (TRU) elements,[5] thorium or a mix. The MSR is one of the six (now seven) classes of reactors that are described as Generation IV (see Pioro 2016) for an overview of Generation IV reactors.

Generation IV refers to the fact that reactor designs are frequently classified into generations. The first commercial nuclear reactors built in the late 1950s and 1960s are classified as Generation I systems. Generation II systems include commercial reactors that were built from 1970 to 1990. Generation III reactors are commercial designs that incorporate evolutionary improvements over Generation II systems. Generation IV is the classification used to describe a set of advanced reactor designs that use non-water coolants and are under development today (MIT 2018).

Those MSRs using thorium are best described as catalytic nuclear reactors (Weinberg and Hammond 1970) because the thorium is fertile, and not fissile, requiring transmutation to uranium before fission. These are denoted Thorium-based Molten Salt Reactors (TMSR) in this paper to separate them from those using uranium only. Within the TMSR class, there are three main categories.

The simplest is the Denatured MSR (DMSR), which is the original TMSR developed at Oak Ridge National Laboratory (ORNL) (Hargraves 2012). This is a single fluid reactor where both fissile uranium and fertile thorium is loaded into the salt and added as required until it cannot sustain fission anymore and the entire salt mixture is replaced, see (Moir and Teller 2005) for details.

The more advanced reactor is the Molten Salt Breeder (MSBR), also started at ORNL, and described in detail by (Robertson et al. 1970). This is a breeder reactor, implying that more fissile material is created than consumed in the fission process, and it consists of two fluids. A representative design is the Liquid Fluoride Thorium Reactor (LFTR). The LFTR consists of a core and a 'blanket,' a volume that surrounds the core. The blanket contains a mixture of thorium tetrafluoride in a fluoride salt containing lithium and beryllium, made molten by the heat of the core. The core consists of fissile uranium-233 tetrafluoride also in molten fluoride salts of lithium and beryllium within a graphite structure that serves as a moderator and neutron reflector. The uranium-233 is produced in the blanket when neutrons generated in the core are absorbed (Hargraves and Moir 2010).

Finally, we have the Molten Salt Fast Reactor (MSFR) developed at CERN, which according to (Siemer 2015) represents the 'best' (most practical/cheap/clean/simple/safe) way to deal with the consequences of a burgeoning human population's addiction to electricity. The MSFR is a better breeder than the MSBR because it operates with higher energies (i.e. the fast spectrum). One of the key motivations for developing this reactor is to eliminate the graphite (Mathieu et al. 2006), which is used in the two aforementioned reactor classes as moderator. However, due to irradiation damages during operation, the graphite has to be replaced periodically. For the 1000 MWe MSBR designed at ORNL, the graphite moderator must be replaced every four years, and around 121 m^3 (272 ton) highly radioactive spent graphite is inevitably produced every time (Robertson 1971). A heavy water-moderated MSR (HW-MSR) solves the graphite issue (Wu et al. 2019). The HW-MSR is also a breeder, but it has a better breeding factor than the MSBR (1.078 versus 1,038) and therefore, it also requires less U-233 initial load.

2.3.1. The history behind and current developments

The idea of a liquid, chemical device instead of the traditional fuel rods in a mechanical device is attributable to the Nobel laureates Eugene Wigner and Harold Urey. It was Wigner who recommended the 'molten fluoride' as the starting-point (Weinberg 1997). Ed Bettis and Ray Briant of ORNL proposed the MSR during the post-World War II nuclear-powered aircraft (MacPherson 1985) project, the Aircraft Reactor Experiment (ARE) (Weinberg 1997), which was stopped in March 1961 soon after John F. Kennedy took office (Rosenthal 2009).

Interestingly, the thorium breeder was mentioned prominently in the 1962 report by the Atomic Energy Commission, stating in the first sentence of the Summary of the Task Force Report (TID-8505) that 'The Molten Salt Reactor has the highest probability of achieving technical feasibility' (MacPherson 1985). Therefore, Alvin M. Weinberg at ORNL lead a team of researchers through the Molten Salt Reactor Experiment (MSRE) that operated between 1965 and 1969 at 7 MWth power level (Moir and Teller 2005) or 8 MWth according to (MacPherson 1985). MSRE operated successfully for 17,655 h[6] (Furukawa et al. 2008) and virtually all nuclear engineering issues were solved (Furukawa et al. 2005).

The direct reason for shutting down the MSRE in 1969 was the satisfactory completion of all experiments. However, when ORNL planned to shift to the next programme of "Molten-Salt Breeder Experiment' in 1976, this new programme Molten Salt Breeder (MSBR) proposal was refused 'for budgetary reasons.' The thorium programme never received the political-or organisational support within the Atomic Energy Commission that the uranium-fuelled fast-breeder received (Weinberg 1997). Furthermore, the LMFBR[7] programme had been spending 'copious government development funds' (MacPherson 1985). This is probably a rewrite for the reality that (Martin 2009) presents;

> Weinberg realized that you could use thorium in an entirely new kind of reactor, one that would have zero risk of meltdown. … his team built a working reactor . … and he spent the rest of his 18-year tenure trying to make thorium the heart of the nation's atomic power effort. He failed. Uranium reactors had already been established, and Hyman Rickover, de facto head of the US nuclear program, wanted the plutonium from uranium-powered nuclear plants to make bombs. Increasingly shunted aside, Weinberg was finally forced out [from his position of Director of Oak Ridge National Laboratory] in 1973.

The uranium fuel cycle offered Pu-239 as a byproduct, which was used for the development of thermonuclear ordnance (Hargraves and Moir 2010). The momentum for thorium-based nuclear energy fell and lingered for decades – a great review of the history of thorium research is provided by (Martin 2012). It is worth noting that Alvin Radkowsky, the Chief Scientist for U.S. Naval Propulsion Program from 1948 to 1972 (Radkowsky 1984), the head of the design team that built the first full-scale commercial nuclear powerplant in Shippingport (Chang 2002) and one of America's most prolific reactor designers (Knight 2008), was a great supporter of thorium-based nuclear power, see (Radkowsky 1984). Decades after the MSRE was shut down, the concept of the TMSR has been slowly advanced by a number of research teams internationally, leading to the number of different designs available today.

The sheer amount of development today is a testimony to the commitment to finding a good, cost-effective nuclear solution. The best overview this author has found is provided by (IAEA 2020). In 2020, there were 10 different consortiums developing various types of MSR technology,

Table 1. Brief overview of developments of MSRs globally by 2020. Source: (IAEA 2020).

Design	Output [MWe]	Type	Designers	Country	Status
Integral MSR	195	MSR	Terrestrial Energy Inc.	Canada	Conceptual Design
smTMSR-400	168	MSR	SINAP, CAS	China	Pre-Conceptual Design
CA Waste Burner 0.2.5	20 (thermal)	MSR	Copenhagen Atomics	Denmark	Conceptual
ThorCon	250	MSR	ThorCon International	International Consortium	Basic Design
FUJI	200	MSR	International Thorium Molten-Salt Forum (ITMSF)	Japan	Experimental Phase
Stable Salt Reactor – Wasteburner	300	MSR	Moltex Energy	UK and Canada	Conceptual Design
LFTR	250	MSR	Flibe Energy, Inc.	USA	Conceptual Design
KP-FHR	140	Pebble-bed salt cooled Reactor	KAIROS Power, LLC	USA	Conceptual Design
Mk1 PB-FHR	100	Fluoride salt-cooled High temperature Reactor (FHR)	University of California at Berkeley	USA	Pre-Conceptual Design
MCSFR	50–1200	MSR	Elysium Industries	USA and Canada	Conceptual Design

see Table 1. Note that (IAEA 2020) counts pebble-bed technologies into the MSR domain, although this paper follows a narrower interpretation of ‘molten salt’.

There are some technological issues left to solve (see Forsberg 2006; World Nuclear Association 2020) for relatively non-technical overviews. Particularly of interest to this paper, is the indirect multi-reheat nitrogen or helium Brayton gas cycle that offers major economic- and technical advantages relative to steam cycles (a Rankine cycle) for electricity production using MSRs (Forsberg 2006).

In summary, (EPRI 2015) finds that the LFTR, which is a specific TMSR technology, exists in the ‘ … late development to early demonstration stages.’ Their finding refers to the Technology Readiness Level (TRL) concept originally developed by the NASA, and later adapted by the U.S. Department of Defense for complex technologies or technology concepts that must perform under extreme environments, such as space flight and armaments. Hence, a decade is a reasonable estimate for maturing this technology as mentioned by several including (Furukawa et al. 2008; Moir and Teller 2005; Weinberg 1997). At the current rate of funding and political support, expected commercialisation is now in the 2030s (World Nuclear Association 2020).

There are many arguments for selecting a TMSR over the uranium-based nuclear power technologies (Furukawa et al. 2008; LeBlanc 2010), but setting aside all the details concerning the various TMSR design with their different advantages and challenges, the advantages across all TMSR designs are taken up in Section 2.3.2, and the challenges are discussed in the section thereafter.

2.3.2. The advantages of TMSR

Perhaps one of the most informative and balanced reports concerning thorium-based nuclear power is (IAEA 2005), although not all are relevant for TMSR. A good report for laymen is (OECD/NEA 2015), where they have clearly separated TMSR from LWR technologies and written in less technical jargon. This paper uses both reports as a point of departure and adds other insights to provide a balanced view concerning the benefits and challenges of TMSRs. To increase the readability, each new topic starts as a paragraph with the key phrase in bold.

Amount of raw material. Thorium is 3–4 times more abundant than uranium and widely distributed in nature as an easily exploitable resource in many countries. Thorium fuels, therefore, both complement uranium fuels and ensure long term sustainability of nuclear power (IAEA 2005), and in the long term replace, or complement, uranium. Uranium-based nuclear power relies on U-235, which constitutes only 0.7% of natural uranium resources (David, Huffer, and Nifenecker 2007), whereas TMSR relies on U-233 and converts the thorium almost completely into energy, such that the real difference is roughly a factor of three hundred times as much output electric power per unit mass of raw fuel ore using a LFTR with closed-cycle gas turbine energy conversion (Juhasz, Rarick, and Rangarajan 2009).

Given the estimates of available thorium at 6.3 million tonnes (OECD/NEA and IAEA 2014), which is probably an underestimated number since thorium has not been the object of a systematic search, it is no overstatement when Nobel laureate in physics Carlo Rubbia states that ‘Thorium constitutes a sustainable energy resource on the human timescale’ (Rubbia 2016). Indeed, a permille of thorium in Earth’s crust (ca 1.2×10^{14} tons of thorium) could electrically power the whole planet for about 20,000 years (Rubbia 2016). A less optimistic estimate, albeit a very positive one as well, is that the thorium resources necessary to produce 900 TWe years will be only 2–3 Million tonnes, if the breeding fuel cycle is established (Furukawa et al. 2008), or 900 years of electricity for the entire world[8] assuming the estimated total supply of 6.3 million tonnes.

Another factor is that using thorium would imply no further demands for mined uranium for several hundred years, although the graphite needs to be changed a number of times in the TMSR (Moir and Teller 2005). They estimate that a present-day LWR reactor would use 38,000 tonnes of mined uranium over 200 years, while a closed-loop TMSR once started up on U-235 and thorium would need only 600 tonnes of mined uranium and could operate for 200 years. 137 tonnes of thorium would be fissioned, and the burnup of the 600 tonnes of uranium and 137 tonnes of thorium would be 18% – compared to just 0.49% for LWRs. A less advanced, once-through thorium reactor would primarily burn uranium, but much more effectively and effectively eliminate the chance for retrieving weapon-grade material. Accordingly, today’s LWRs each require 5700 tonnes of mined uranium over 30 years for a 1000-MWe nameplate effect. A once-through TMSR in 30 years of operation at 75% capacity factor with the same nameplate effect would consume by fission, 17 tonnes of thorium, 3.8 tonnes of U-238, and 6.7 tonnes of U-235. This requires 1500 tonnes of mined uranium with a burnup of 13.7%. The fuel situation is extremely good for TMSR regardless of the chosen design.

A relevant fact is that a 1000 MWe coal plant generates about 13 tonnes of thorium per year in its ash. One tonne of thorium can generate in turn 1000 MWe in a well-optimised thorium reactor. Thus, the ashes of a single coal power plant can conceptually fuel 13 thorium plants of equivalent power (Rubbia 2013). This can be a useful fact for countries that have no thorium resources, and it can be useful in the transition from a fossil-fuelled society to one using thorium-based nuclear energy. However, the largest source of thorium as a by-product comes from the current mining operation of titanium and Rare Earth Elements (REE). As (Ault et al. 2016) state:

> The estimated 90 000 tonnes/yr of by-product thorium that could be recovered from active mines (80,000 tonnes/yr of this coming from titanium mines alone) would be sufficient to satisfy the annual thorium demand—even using the most thorium-resource-inefficient nuclear fuel cycle for all the world’s nuclear reactors—more than six times over.

Hence, the fact is that there are large amounts of thorium wasted from other processes that are sufficient to generate huge amounts of energy with no additional raw material extraction costs. However, the literature is silent on the fact that uranium in seawater impacts this discussion – although the content of thorium in seawater is unclear. The argument that thorium is significantly more abundant is not substantiated with the current state of knowledge.

Waste. The thorium fuel cycle is an attractive way to produce long term nuclear energy with low radiotoxicity waste for several reasons. First, compared to traditional nuclear reactors which ‘burn’ the fissile uranium isotope U-235 the TMSR uses fissile U-233 which is derived from Th-232 in the reactor itself. Whereas U-235 constitutes only 0.71% of mined natural uranium and requires enrichment, practically all the thorium can be converted to U-233, and no enrichment is needed (Juhasz, Rarick, and Rangarajan 2009). The process of deriving the U-233 from Th-232 can take place in two principal ways. The basic approach is to use mined and enriched U-235 or to use discharged LWR spent fuel, particularly Pu-239. This gives the startup conditions and burnup rates calculated by (Moir and Teller 2005), mentioned above. This seems to indicate that both the once-through TMSR and the closed-loop TMSR are significantly better than the LWRs in most respects.

The most advanced approach, however, would be to eliminate uranium altogether. For example, it is possible to use a 1 GeV and 200–300 mA proton accelerator to start the reactor (Furukawa et al. 2005; Furukawa et al. 2008). Others approach also exist, see (Schaffer 2013).

Second, the transition to thorium could be done through the usage of weapons-grade plutonium or civilian plutonium (IAEA 2005). The safe usage alternative of this plutonium is actually one of the reasons for the interest in MSRs in Japan (MacPherson 1985). Indeed, the reactor can use a variety of fuels (U-233, Enriched uranium (U-235), Pu-239), and even TRU can serve as supplementary fuel (Furukawa et al. 2008). Furthermore, the total amount of these TRU elements produced in the same condition is 0.3 g from a TMSR of the FUJI design, which is much smaller than the 25 kg produced from uranium-based LWR. However, in the back end of Th-232–U-233 fuel cycle, there are other radionuclides such as Pa-231 and Th-229, which may have long term radiological impact (IAEA 2005) although the total amount is far less for TMSR than for any reactors in operation today. Consequently, there is a drastic reduction in the radioactive life span of the waste. As (Kamei 2011) writes:

> It takes about one million years for the spent uranium fuel without reprocessing to be the same radioactive toxicity of natural uranium. Even with reprocessing, it will need about 100 thousand years. However, it is estimated to be about a few hundred years for the thorium fuel because production amount of americium and curium is very small.

Third, the drastic reduction in the life span of the waste makes storing spent fuel easier. The long-term interim storage and permanent disposal in a repository of spent thorium-based fuel are simpler than for uranium-based fuel without the problem of oxidation (IAEA 2005). Also, the sheer amount of storage space required is reduced approximately hundredfold (David, Huffer, and Nifenecker 2007).

Finally, thorium is not commercially used as nuclear fuel. It is left as radioactive waste after mining for rare earth minerals and – metals, which become environmental and social issues within the resource-rich countries (Kamei 2011). It is important to note that thorium has very low radioactivity. As (Martin 2009) writes; ‘It’s only slightly radioactive; you can carry a lump of it in your pocket without harm’. Nevertheless, by using thorium as nuclear fuel this issue is also solved.

Safety. Unlike the traditional reactors, TMSRs cannot ‘fuel melt down’ (Furukawa et al. 2008; Juhasz, Rarick, and Rangarajan 2009; LeBlanc 2010). It is technically impossible because TMSRs have passive safety. Furthermore, molten fluorides are stable to the reactor irradiation, because they are simple ionic liquids, and do not undergo any violent chemical reactions with air or water (Furukawa et al. 2008). Also, the initial fuel needed, including the amount circulating outside the core, is considerably less than half that of other breeding reactors such as the liquid metal–cooled fast reactor[9] (Moir and Teller 2005).

Another significant safety mechanism gives small, excess reactivity, about 2% (Moir and Teller 2005), because there is no need for xenon override, and with online refuelling there is no need to make provision for fuel consumption. Thus, there is no chance for large power surges, an important safety concern in LWR (Furukawa et al. 2008; LeBlanc 2010) because LWRs typically have about 20% excess reactivity (Moir and Teller 2005).

The online refuelling is also combined with a continuous removal of matter, which is beneficial for two reasons. The first is that most gaseous fission products (Xe, Kr, etc.) are continuously removed so there is no danger of release of these radioactive products, even under accident conditions (Furukawa et al. 2008; LeBlanc 2010; Moir and Teller 2005). If Xe-135 is allowed to burn off, the nuclear chain reaction will accelerate, which requires control rods to be reinserted in a carefully managed cycle until the reactor is stabilised. Mismanagement of this procedure contributed to the instability in the Chernobyl core that led to a runaway reactor and the explosion that followed (Hargraves and Moir 2010). Continuous removal of Xe-135 is therefore a great safety mechanism in itself. The second reason is that the fission products either quickly form stable fluorides that will stay within the salt during any leak or accident or are volatile or insoluble and are continuously removed (Furukawa et al. 2008; LeBlanc 2010).

Fail-safe solution. In the case of a loss of electrical power (case of the accident at Fukushima I, Japan, 11 March 2011) a freeze plug melts releasing the fuel to a passively cooled drain tank, surrounded by borated water, ensuring automatic shutdown (Furukawa et al. 2008; Greaves et al. 2012). The freeze plug safety feature is as old as the MSRE, yet it meets the latest NRC's requirement. Unlike virtually all other reactors, the TMSR needs the power to prevent its shutdown (Hargraves and Moir 2010), which means that a loss of power will automatically lead to a shutdown.

Energy conversion efficiency. The energy efficiency issue has two aspects. One being the reactor itself and the second is the conversion of thermal energy to electricity. Concerning the reactor itself, the absorption cross-section for thermal neutrons of Th-232 (7.4 barns) is nearly three times that of U-238 (2.7 barns). Hence, a higher conversion (to U-233) is possible with Th-232 than with U-238 (to Pu-239) (IAEA 2005; Kazimi 2004). Thus, thorium is a more 'fertile' material than U-238 in thermal reactors, but thorium is inferior to depleted uranium as a 'fertile' material in fast reactors (IAEA 2005).

However, thorium provides more flexible breeding because, for the 'fissile' U-233 nuclei, the number of neutrons liberated per neutron absorbed is greater than 2.0 over a wide range of thermal neutron spectrum. Thus, contrary to the U-238–Pu-239 cycle in which breeding can be obtained only with fast neutron spectra, the Th-232–U-233 fuel cycle can operate with fast, epithermal or thermal spectra (IAEA 2005).

Another aspect of the reactor is the utilisation of fuel. LWR typically utilises only 5% of the material before they must be replaced due to radiation damage, that is, a safety issue, (Greaves et al. 2012). The TMSR, however, is free from problems of structural radiation damage and can, in principle, therefore go on until all fuel is utilised. However, some TRU is generated as mentioned before, but it constitutes a negligible fraction in terms of mass.

Furthermore, the high temperature of the fuel salt[10] permits higher conversion efficiency (Furukawa et al. 2008), and from the nuclear-thermal conversion, the conversion into electricity is also better. The TMSR can likely convert thermal energy into electricity with 45% efficiency, compared to 33% typical of coal and older nuclear plants (Hargraves and Moir 2010), 43% (Moir and Teller 2005) and 44% (Greaves et al. 2012) are also used. Importantly, these numbers concern designs from the 1960s.

In the 1960s designs, high-temperature heat is inefficiently dumped to lower temperatures to match what the steam cycle could tolerate, which reduces heat exchanger efficiency significantly (Forsberg 2006). Since then, gas Brayton power cycles have been developed by the aircraft industry and also used widely in the utility industry with natural gas as preferred fuel (Forsberg 2006). Therefore, most Generation IV energy conversion systems, including TMSR, are based on the Closed Cycle Gas Turbine (CCGT) power cycle, that is, the Closed Brayton Cycle (CBC) (Juhasz, Rarick, and Rangarajan 2009), which reduces the inventory of fuel salt in the TMSR by up to 50% (Peterson

2003). Such reduction in fuel salt inventory is highly beneficial for waste, proliferation resistance and safety.

Furthermore, the adoption of closed helium or nitrogen Brayton power cycles enables the power cycle to efficiently use the high-temperature heat generated by the TMSR (Peterson 2003), resulting in a 15% improvement in electrical output without changing the temperatures of the fuel salt exiting the reactor core (Forsberg 2006). Hence, the gas Brayton cycles are now often assumed the best fit to TMSR. This offers further advantages for tritium management because removing tritium from gas is far easier than from steam, and with the newest Ultra Super Critical cycles the efficiency could approach 50% if coupled to TMSR (LeBlanc 2010).

Hence, almost a 50% increase in CCGT plant efficiency can be realised, when compared to the highest efficiency achievable with the steam cycle (Juhasz, Rarick, and Rangarajan 2009). Some researchers, therefore, foresee that the efficiency could become exceptionally high with thermal efficiencies from 55% to potentially in excess of 60% by using multiple-reheat Brayton cycles while enhancing safety and economics at the same time (Peterson 2003). Indeed, from an economic viewpoint, the higher power density of gas turbines helps reduce capital costs by almost a factor of 2 compared to a steam turbine.

Proliferation resistance. When the idea of thorium power was first revived in recent years, the initial focus was its inherent proliferation resistance, see (Kazimi 2004), while using traditional solid fuel reactors. However, there are more non-proliferation advantages using the TMSR (Furukawa et al. 2008). Principally, the U-233 produced from Th-232 is necessarily accompanied by U-232, a proliferation prophylactic (Hargraves and Moir 2010). U-232 is highly radioactive and has unusually strong and penetrating gamma radiation (2.6 MeV), making diversion of this fuel for misuse extra difficult and easier to detect if stolen (Moir and Teller 2005). Furthermore, about 50 tonnes of fuel salt is necessary for extracting 1 SQ (Significant Quantity for weapons), which is more than the total inventory of a 160 MWe reactor (Furukawa et al. 2005).

Due to the inherent proliferation resistance, TMSR meets the requirements of the Generation IV nuclear power plants as spelled out in the Energy Policy Act of 2005 (Juhasz, Rarick, and Rangarajan 2009). Indeed, Tatsujiro Suzuki, a member of Japan Atomic Energy Committee, proposed in 2009 using thorium-MOX (mixed oxide) fuel in today’s commercial LWRs to secure nuclear non-proliferation and disarmament (Kamei 2011).

Other benefits. Reactor core heat can also be used for producing hydrogen (Furukawa et al. 2008; Juhasz, Rarick, and Rangarajan 2009). Such a byproduct can be useful for many applications including as fuel for engines. TMSRs are also suitable as engines because the molten fluoride salts are excellent coolants, in general, with a 25% higher volumetric heat capacity than pressurised water and nearly five times that of liquid sodium (LeBlanc 2010). In other words, much more compact designs are possible, which is highly beneficial for example for use in marine applications (see Emblemsvåg 2021b).

2.3.3. The challenges of TMSR

The biggest challenges are not technical, but the public perception of the nuclear industry itself, based on the historical path. The historical reasons have led to the fact that the database and experience of thorium fuel cycles are very limited, compared to uranium- and plutonium fuels, and need to be augmented before large investments are committed for commercial utilisation of thorium fuels and fuel cycles (IAEA 2005). Furthermore, the fluid fuel reactor concept has not been popular, and only the TMSR have been successful of the fluid fuel reactors in the past (Furukawa et al. 2008). These two challenges have probably impacted each other.

Remaining work at ORNL. Inaccurate information regarding unfinished work regarding the MSRE remains. For example, the corrosion problems are solved and (Rodriguez and Sundaram 1981) were one of the few to try to rectify this (Furukawa et al. 2008). Additionally, significant progress is made in the past 15 years in the development of corrosion-resistant materials by acting on the composition, surface condition, and secondary treatment of the materials (Rubbia 2016).

Naturally, there are other issues to address. A very useful overview is provided by (Forsberg 2006) and he writes 'The commercial viability of the TMSR has improved both in absolute terms and in comparison with other reactor concepts. However, significant work is required before definitive conclusions can be made about the economics, advantages, and disadvantages of the TMSR relative to those of other advanced reactor concepts.'

Radiation risk. Opinions vary. As noted by (IAEA 2005), the irradiated thorium-based fuels contain a significant amount of U-232. As a result, there is a significant buildup of radiation exposure associated with storage of spent thorium-based fuel or separated U-233, necessitating remote and automated reprocessing and refabrication in heavily shielded hot cells and increase in the cost of fuel cycle activities.

Another issue voiced by the (IAEA 2005) is that in the conversion chain of Th-232 to U-233, Pa-233 is formed as an intermediate, which has a relatively longer half-life (about 27 days) compared to Np-239 (2.35 days) in the uranium fuel cycle thereby requiring longer cooling time of at least one year for completing the decay of Pa-233 to U-233. Normally, Pa is passed into the fission product waste in the THOREX process,[11] which could have long-term radiological impact. It is essential to separate Pa-233 from the spent fuel solution prior to the solvent extraction process for the separation of U-233 and Th-232, because Pa-233 is a major neutron absorber (World Nuclear Association 2020).

Fuel reprocessing. Although the physics of these two statements are true, they are insignificant to the TMSR, but highly applicable for thorium-based LWRs. First, remote- and automated solutions are today used in nuclear facilities but most likely not necessary in TMSRs since the fuel can be pumped to wherever it is wanted.

Second, by using online feeding and offline reprocessing the amount of fuel in the reactor is very limited and the two aforementioned issues are only relevant *if* the reactor suffers an unplanned stoppage for whatever reason, and cannot be restarted, before the fuel is utilised. The improvements in technology have been staggering in this respect. In the MSBR experiment, which was cancelled in 1976, the amounts of salts in the daily reprocessing were 4000 litres with a 10-day reprocessing time. Today, the CNRS-Grenoble in France has proposed an innovative concept called TMSR-NM (Non-Moderated) without graphite core where the daily reprocessing is reduced to merely 40 litres (Delpech et al. 2009). However, fuel reprocessing is also one of the areas that need more research to improve solutions.

Further research. In summary, there are no issues preventing successful, further research and development of TMSR. Naturally, there are engineering issues left to solve, as mentioned, but no gamestoppers (see IAEA 2005; OECD/NEA 2015). In fact, this author has not found a single, serious publication that does not support further research and development of TMSR. The main discussions concern type of reactors and therefore how much research and development is left to mature the technology. Thus, 'Individually, the advantages are intriguing. Collectively they are compelling' (Hargraves and Moir 2010).

A challenge that requires attention is not a technical challenge *per se* but related to the availability of fuel, as discussed next.

2.3.4. The availability of fissile material for implementation

A significant challenge with implementing MSRs based on the Th-232-U-233 fuel cycle is the fissile fuel supply since there is no available U-233 (Zou et al. 2018). Therefore, it is important to keep in mind that thorium-based nuclear power comes in three major technology levels, and many publications are unclear about this – a good exception is (OECD/NEA 2015). Figure 2 provides a rough overview and also the timescales related to development based on this author's impression from studying the literature.

One approach is that current nuclear technologies can be retrofitted with solid thorium fuel (Radkowsky and Galperin 1998). Indeed, the (IAEA 2005; OECD/NEA 2015) point out that in the short term, it should be possible to incorporate the thorium fuel cycle in all existing thermal and fast reactors, which accounts for the large share of reactors today, without major modifications in the engineered systems, reactor control and the reactivity devices. In fact, The U.S. Nuclear Regulatory Commission (NRC) (see Ade et al. 2014), did

> … summarize historical, current, and proposed uses of thorium in nuclear reactors; provide some important properties of thorium fuel; perform qualitative and quantitative evaluations of both in-reactor and out-of-reactor safety issues and requirements specific to a thorium-based fuel cycle for current LWR (Light Water Reactor) designs; and identify key knowledge gaps and technical issues that need to be addressed for the licensing of thorium LWR fuel in the United States, and concluded that 'Despite the number of gaps identified, the process and review have indicated that by the use of exceptions (similar to what has been done for MOX fuel), thorium potentially could be licensed under the current regulations without additional rule making'.

It is interesting to note that some of the first commercial LWRs developed in the late 1950s and early 1960s in the United States were initially operated with thorium-based fuels (OECD/NEA 2015). In fact, 3 thorium reactors have been operating for longer periods already (Kazimi 2004) and more are planned (Schaffer 2013). The first was a gas-cooled, graphite-moderated reactor called Peach Bottom Unit One, located in Pennsylvania, which used a combination of thorium and highly enriched uranium in the mid-1960s. Then, another gas-cooled reactor at Fort St. Vrain in Colorado was run on a similar thorium-based fuel between 1976 and 1989. Lastly, was the German THTR-300 – a high-temperature gas-cooled, 300-megawatt reactor outside Hamburg which operated in the 1980s.

Thus, thorium-based fuels for the current fleet of reactors work, but the current solid fuel reactors will also provide a number of fissile materials that can be used to start TMSRs. With the quantities of nuclear material generated from the nuclear industry so far, there is enough to start up a large number of TMSR that will generate energy for several hundred years (Moir and Teller 2005).

Both India and China are also working on the same issues. In India, according to (Vijayan 2013): the first stage consists of using natural uranium PHWR; the second stage is planned using the plutonium and depleted uranium extracted from the PHWR in FBRs; and at the third stage, with U-233

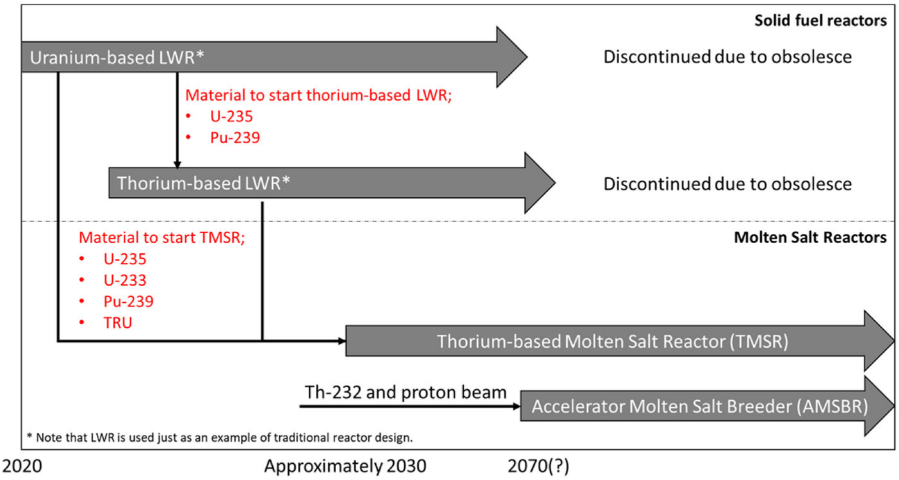

Figure 2. Major technology implementation roadmap.

produced from the second stage, TMSRs will be deployed. In fact, India plans to meet 30% of its total power requirements in 2050 by using thorium-fuelled reactors (Schaffer 2013).

In 2011, the Chinese Academy of Sciences launched the TMSR nuclear energy system project with aims to develop solid- and liquid-fuelled MSRs and for realising effective thorium energy utilisation and hydrogen production from nuclear energy within 20–30 years (Jiang, Xu, and Dai 2012). The approach discussed by (Zou et al. 2018) fits well into this programme. They analyse two different avenues and find that by deploying a fleet of TMSRs with various functions, a closed thorium fuel cycle could be achieved in two steps. The TMSRs at the first step are to use Pu or TRUs transmuting to U-233 as a fuel outside the core (after initial fissions are started) while the second step is to operate with thorium fuel cycle directly for iso breeding or breeding TMSRs inside the core.

However, as represented in Figure 2 the research suggests that the long-term technology is the Accelerator Molten-Salt Breeder (AMSBR) in conjunction with a TMSR. The AMSBR uses naturally occurring thorium as fuel, and it will provide fissile material also for the TMSRs. Such a combination will essentially offer an energy solution that will provide humanity with energy for thousands of years, but it is currently too costly (Schaffer 2013). Furthermore, it is in early development stage so that 'deployment of the third phase is foreseen beyond 2070' (Vijayan 2013). However, the advent of the AMSBR is not critical, because there is enough fissile material to use in the world today for decades of operations.

3. Comparative cost analysis

Levelized Cost of Energy[12] (LCOE) has many issues, but improved methods are still not used in decision-making (Doemeland and Trevino 2014). It is widespread and used for policymaking worldwide (IRENA 2012), but LCOE is generally treated as a definite number and the assumptions lying beneath that result are rarely reported or even understood (Darling et al. 2011). For a brief introduction to LCOE – the interested reader is referred to (Emblemsvåg 2020, 2021a; Reichenberg et al. 2018; Ueckerdt et al. 2013) for reviews of challenges and how they can be handled in different contexts.

The standard formula used for calculating the LCOE is (IRENA 2012):

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} I_t + M_t + F_t/(1+r)^t}{\sum_{t=1}^{n} E_t/(1+r)^t} \tag{1}$$

where LCOE is the the average lifetime levelized cost of energy generation; I_t is the investment expenditures in the year t; M_t is the operations and maintenance expenditures in the year t; F_t is the fuel expenditures in the year t; E_t is the electricity generation in the year t; r is the discount rate; and n is the economic life of the system. For dispatchable energy sources, this formula is straightforward. The issues that cause discussions are typically the life of the asset, what discounting factor to use due to the high capital expenditures and cost escalations. Costs are addressed next for LWRs and then for TMSR in Section 3.2.

3.1. LWR costs

When it comes to LWR costs, there are a couple of issues to address. First, nuclear power is capital intensive, in general. The capital costs account for at least 60% of the LCOE (World Nuclear Association 2019), which means that the LCOE is sensitive to the discounting factor and the life-span. The sensitivity towards the discounting factor is shown in Table 2. The discounting factor is best calculated using the Weighted Average Cost of Capital (WACC) formula (Emblemsvåg 2003).

Comparing the numbers in Table 2 to the LCOE estimates in (US EIA 2019b), large discrepancies are found. LWR is estimated to have an LCOE (including tax credits) of about 77 USD/MWh with a range of 73–81 USD/MWh, which is consistent with the high US numbers in Table 2, but

Table 2. Projected nuclear LCOE costs for plants built 2015–2020 [USD/MWh] using average numbers for China: (World Nuclear Association 2019). The 4.5% column is a linear interpolation performed by the author.

Country	At 3% discount rate	At 4.5% discount rate	At 7% discount rate	At 10% discount rate
Belgium	51.5	63.8	84.2	116.8
China	28.2	33.5	42.4	56.6
Finland	46.1	57.9	77.6	109.1
France	50.0	62.2	82.6	115.2
Hungary	53.9	67.4	89.9	125.0
Japan	62.6	72.0	87.6	112.5
South Korea	28.6	33.0	40.4	51.4
Slovakia	53.9	65.2	84.0	116.5
UK	64.4	78.1	100.8	135.7
USA	54.3	63.1	77.7	101.8

more than twice as high as those reported by countries that build LWR more cost effectively such as South Korea and Finland. The (MIT 2018) has even higher LCOE estimates.

There are three issues to discuss in this context. First, the discounting factors used are too high. This has the effect of lowering the LCOE, which means that other factors are even higher. The (MIT 2018), for example, used 7.9%. However, 7.9% is unrealistic over the life span of any long-term investment. In fact, (Estrada 2014) finds that '… average across the 19 countries in the sample, stocks provided investors with an annualized real return of 4.7%, 3.8 percentage points higher than that of bonds (0.9%)', and this finding was based on the very large Dimson-Marsh-Staunton dataset, which covers 19 countries over 110 years. US stocks from 1802 to 2002, had a total annualized return of 7.9% (Arnott 2003) whereas a third data set across 17 countries from 1900 to 2005 averaged approximately 5% (Dimson, Marsh, and Staunton 2008). In short, investors cannot expect the same Return of Equity (ROE) for such investments than for short-term investments, which makes sense because of the powerful time diversification, see (Bernstein 1976).

Note that there are cases where the project execution has taken a very long time which in combination with very high capital charges, high WACC, has resulted in very large costs, such as in the Hinkley Point C project – (see National Audit Office 2017) for a complete review.

Assuming 7.9% as ROE, which is historically high, 4% interest rate on debt, 23% corporate tax rate[13] and the 30%/70% equity/debt ratio (World Nuclear Association 2019) uses, then the WACC becomes 4.5%. About 4.5% is more aligned with the practice found in Ontario, Canada, where the real social discount rate (SDR) range used is 2–8%, with an individual's SDR being 3.5% to 4.5% (Ontario Power Authority 2008). A simple linear interpolation between the 3% LCOE and the 7% LCOE in Table 2, gives the corresponding an LCOE to the 4.5% WACC of 63 USD/MWh for the US. For South Korea, it would become 33 USD/MWh.

Second, (MIT 2018) and others claim that the nuclear industry has a cost escalation problem. However, Table 2 shows a large spread of LCOE between the countries is found. In China it is estimated that building two identical 1000 MWe reactors on a site can result in a 15% reduction in the cost per kW compared to that of a single reactor (World Nuclear Association 2019).

Indeed, (Lovering, Yip, and Nordhaus 2016) review a number of interesting cases. First, between 1954 and 1968, 18 demonstration reactors were built in the US and the Overnight Construction Costs (OCC)[14] fell by 81%. In this period the reactors increased from 80 MW to 620 MW. Hence, economies of scale were important. Then, there were some turnkey contracts between 1964 and 1967 with reactors between 800 MW to 1,100 MW, and the OCC fell by 33%. Second, from 1960 to 1969 in Japan, reactors increased in size from 300 MW to 700 MW, and costs fell by 82%. In South Korea, costs fell by 50% from the first reactor in 1971. Hence, these results show that there is no single or intrinsic learning rate for nuclear power technology, nor an expected cost trend.

This suggests that the way costs evolve over time appears to be dependent on different learning curves, factors such as utility structure, reactor size, national regulatory regimes and international collaboration (Lovering, Yip, and Nordhaus 2016). The challenge is to separate the increases in reactor size from the learning curve effects of building a number of similar reactors because the number of replicas built is so low. The industry has therefore introduced the Nth Of A Kind (NOAK) concept with corresponding assumptions, where the accumulated installed capacity is measured. NOAK is currently defined as '… the nth-of-a-kind or equilibrium commercial plant of identical design to the FOAK plant and is defined as the next plant after the unit that achieves 8.0 GWe of capacity' (EMWG 2007) where FOAK is First Of A Kind. This concept, however, does not necessarily provide the same cost advantages as factory production, which would lower costs much more.

Concerning the quality of estimates, (EMWG 2007) argues that '… highly innovative nuclear energy systems, such as the Lead-Cooled Fast Reactor (LFR) or the Molten Salt Reactor (MSR), are likely to have their early estimates prepared with cost-scaling equations, using formulas to account for indirect and support costs' and that 'top-down approaches use simpler models than the ORNL bottom-up approach adopted for the 1993 evaluation of the MHTGR and LMR'. Hence, the detailed cost estimates by ORNL are good, which is why they form the basis for the work presented in this paper.

The relatively low-cost estimates presented in Table 3, therefore, support the findings of (Lovering, Yip, and Nordhaus 2016) that there is no inherent cost escalation trend associated with nuclear technology. Thus, if the nuclear industry has a cost issue, it is not inherent to the technology *per se* but rather a societal issue.

The huge cost increases seen in the US, in particular, have come in response to incidents and the Three Mile Island accident. The result is prolonged project duration, legal costs and more, see (Lovering, Yip, and Nordhaus 2016). In comparison, the costs of French reactors did not change must after the Chernobyl disaster, and in South Korea costs have actually been falling. Minimising the OCC is key (Lovering, Yip, and Nordhaus 2016; World Nuclear Association 2019), and stable regulatory regime, standardised design and factory production will cut these costs substantially. Exactly, how much is difficult to estimate although (Delene et al. 1999) provide some heuristics that can be useful.

Table 3. Cost parameters for a 1000 MWe power plant as defined in 1978, using information from (Delene 1994; Engel et al. 1980; Moir 2002) for 1978 and 2000 numbers. 2020 is the work of this author.

Nominal USD	1978			2000			2020		
Item	TMSR	PWR	Coal	TMSR	PWR	Coal	TMSR	PWR	Coal
Direct cost									
Land and land rights	2	2	2	5	5	5	7	7	7
Structure & improvements	124	111	245	301	269	594	451	403	890
Reactor plan equipment	180	139		437	337		655	505	
Turbine plan equipment	100	113	88	243	274	213	364	410	319
Electric plant equipment	54	44	31	131	107	75	196	160	112
Miscellaneous plant equipment	17	13	11	41	32	27	61	48	40
Main conditioning heat reject	14	22	14	34	53	34	51	79	51
Total direct costs [MUSD]	491	444	391	1192	1077	948	1786	1613	1420
Indirect cost									
Construction services	75	70	39	182	170	95	273	255	142
Home office engineering services	53	53	16	129	129	39	193	193	58
Field office engineering & services	34	30	10	82	73	24	123	109	36
Total indirect costs [MUSD]	162	153	65	393	372	158	589	557	237
Total costs [MUSD]	653	597	456	1585	1449	1106	2374	2171	1657
Capacity factor	90%	80%	80%	90%	80%	80%	90%	80%	80%
Normalized cost [cents/kWh]									
Capital	0.83	0.85	0.65	2.01	2.07	1.58	3.01	3.10	2.36
Operations & Maintenance (O&M)	0.24	0.47	0.33	0.58	1.13	0.80	0.87	1.69	1.20
Fuel	0.46	0.31	0.71	1.11	0.74	1.72	1.66	1.11	2.58
Waste disposal	0.04	0.04	0.04	0.10	0.10	0.09	0.15	0.15	0.13
Decommissioning	0.02	0.03		0.04	0.07		0.06	0.10	
TOTAL [cents/kWh]	1.59	1.70	1.73	3.84	4.11	4.19	5.75	6.15	6.27

Third, (MIT 2018) and others use 30 years economic life-span. However, the US fleet in 2019 already had an average age of 38.6 years[15] and operated at Power Capacity Factor (PCF) of 93.4% (US EIA 2019a). Indeed, the majority of operating US commercial nuclear power plants have obtained an initial license renewal to extend reactor lifetime from 40 to 60 years (Gormley, Sinkiewicz, and Wolfe 2020; OECD/NEA 2012).

3.2. TMSR energy costs

This paper does not advocate a specific TMSR design because specificity is not possible to maintain concerning all the cost data since there is little published material (Mignacca and Locatelli 2020). Thus, it is necessary to be pragmatic and collect sufficient data to produce relatively robust cost estimates given the current technology maturity. The TMSR for which there is most available data is the ORNL design. Furthermore, the thermal efficiency is assumed to be about 44% for a TMSR using steam turbines (Greaves et al. 2012). This number can become higher, as discussed earlier, but since the argument presented here relies on older data, the efficiency data must match them to avoid misrepresenting the facts.

The researchers at ORNL made very comprehensive cost calculations to estimate the capital expenditures and the operating expenses, but they did not calculate the cost of the electricity. Using their information, (Moir 2002) calculated the cost of electricity and found the TMSR to be competitive with 3.8, 4.1 and 4.2 ¢/kWh for TMSR, PWR and coal, respectively (see Table 3). Note that these calculations do not include current safety, licensing, and environmental standards, which will impact costs, as will CO_2 sequestering and increased HAP (Hazardous Air Pollutants) for coal. The capacity factor is stated as 90% for the TMSR to account for the reduced down-time because of its online fueling feature and 80% for the PWR (Moir 2002).

Furthermore, this calculation is 20 years old, so an update is necessary. The inflation from 2000 to 2020 is estimated to be 49.8%.[16] Since (Moir 2002) does not calculate the LCOE numbers, this is calculated next and represents a contribution of this paper to the literature.

3.3. LCOE analysis

For dispatchable energy sources using the LCOE formula is simple because the capacity modelling is simple. Then, by using the cost estimates in Table 4, the LCOEs can be estimated. However, given the realistic life-span of nuclear power plants, it is common to undertake a major refurbishment after ca 30 years (OECD/NEA 2012) often involving replacing electricity generating equipment. The costs are therefore large and could easily become 60% of the initial investment in real terms. This gives a cost cash flow for the TMSR as shown in Figure 3 where the refurbishment impact

Table 4. LCOE for PWR and TMSR for various life-span and WACC.

	LWR LCOE [USD/MWh]		US	63.1	South Korea	33.0
	Base year	2020	Adjusted for US		Adjusted for South Korea	
Life span	TMSR	PWR	TMSR	PWR	TMSR	PWR
At 4.5% WACC						
30 years	44.92	52.94	53.51	63.08	28.02	33.03
60 years	35.24	41.50	41.98	49.45	21.98	25.89
Difference	9.68	11.44	11.53	13.63	6.04	7.14
Reduced LCOE	27%	28%	27%	28%	27%	28%
At 10% WACC						
30 years	37.53	43.41	44.71	63.08	23.41	33.03
60 years	23.43	26.79	27.91	38.93	14.62	20.38
Difference	14.10	16.62	16.80	24.15	8.80	12.64
Reduced LCOE	60%	62%	60%	62%	60%	62%

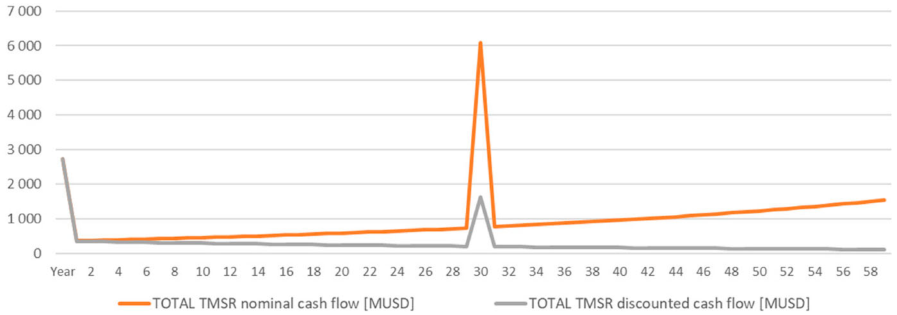

Figure 3. Life Cycle Cost Cash Flow Profile [MUSD] for 60 Years of Operation. Note that the PWR has a similar profile.

is assumed to be fully incorporated in Year 31. Note that the nominal costs increase by time due to inflation while the same discounted costs fall since the WACC is greater than inflation. Also, note how the initial investment costs are the major costs. The other costs are relatively small in comparison.

Using this cash flow profile and the 4.5% discounting factor, the LCOE is presented in Table 4. Since most LWR are PWRs, the results can be used interchangeably for LWR and PWR; the accuracy required to distinguish between the two is lacking. It is more interesting to compare PWR to the TMSR. Furthermore, the numbers used directly from Table 3 lack the regulatory costs since the Three Mile Island accident and later, and they are shown to the left in Table 4. However, by using linear adjustment, the current LWR LCOE at 4.5% and 30-year life-span, other costs are scaled as shown in the shaded cells in Table 4.

Clearly, despite the large refurbishment costs in Year 31, there are significant reductions in the LCOE when increasing the life span from 30 years to 60 years. Using the simple adjustment for stricter rules and regulations, the TMSR comes out at ca 53 USD/MWh, which is less than half of the estimate provided by (MIT 2018), which is about 120 USD/MWh. The difference becomes even larger for South Korean numbers and 60 years life-span.

These large differences are largely driven by life-span and the cost numbers from which the LCOE is calculated. Some, including (MIT 2018), claim that the estimates of (Engel et al. 1980) are highly uncertain because they are based on early pre-conceptual designs, but they seem to ignore that the TMSR at ORNL were operational for thousands of hours with 80% uptime over 15 months (Haubenreich and Engel 1970). They also ignore the work of (Delene 1994; Delene et al. 1999). The result is that (MIT 2018) estimates capital expenditures of 6.1 bn USD for a 1,000 MWe TMSR. This is more than twice the numbers in Table 2 and much higher than other estimates found by (Mignacca and Locatelli 2020). Since the numbers from ORNL are based on actual, detailed cost analysis from a reactor that worked well as a prototype, they are most likely more trustworthy.

Given such uncertainty, uncertainty must be added into the model and a Monte Carlo simulation is performed to assess the impact of uncertainty using 50,000 trials. For details concerning Monte Carlo simulations, the interested reader is referred to (Emblemsvåg 2003). With the TRL described by (EPRI 2015), triangular uncertainty distributions are used where the minimum and maximum values are ±20% from the mean except for the power capacity factors where ±10% from the mean is used.

Figures 4 and 5 present the results. Note that both figures contain the reference numbers from Table 2 from both the US and South Korea. The results shown are in the same ballpark range as the studies discussed by (Mignacca and Locatelli 2020) in their review, except (MIT 2018).

Given the differences in the US and the South Korean approach described by (Berthélemy and Escobar Rangel 2015; Lovering, Yip, and Nordhaus 2016), there are significant savings to be achieved as discussed earlier. Such effects are ignored here, which illustrates that the 2 USD/Watt CAPEX target and the 30 USD/MWh OPEX target expressed by (Hargraves 2012) may be achievable once the TMSR technology reaches the NOAK level and certainly once it has been

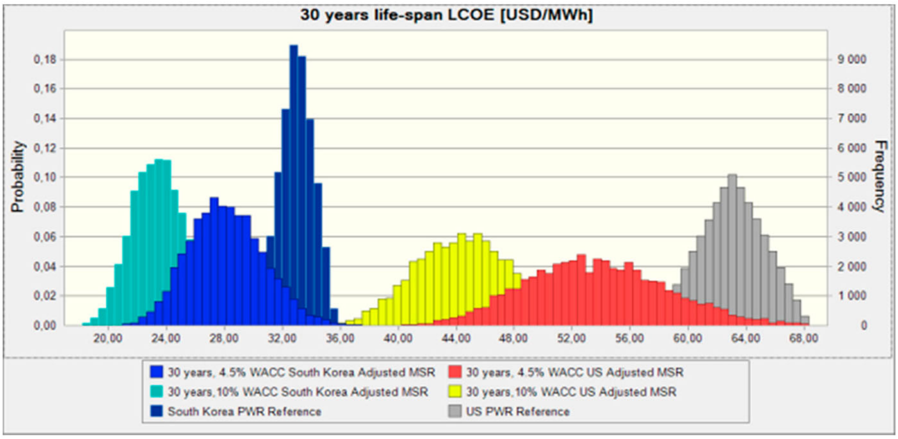

Figure 4. LCOE over 30 years life-span under the US and South Korean contexts using a WACC of 4.5%.

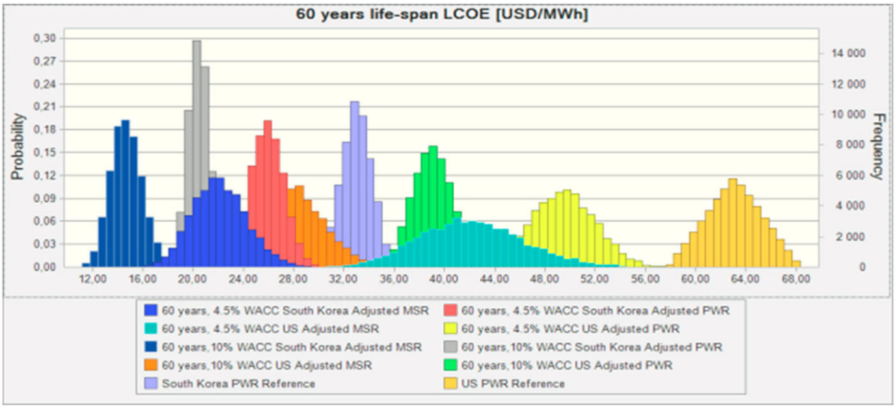

Figure 5. LCOE over 30 years life-span under the US and South Korean contexts using a WACC of 10%.

industrialized and manufactured as products. Hence, with a high degree of confidence, TMSRs are found to provide safe, clean, proliferation resistant and cost-effective energy for sustainable development.

4. Implications and directions for future research

The research presented in this paper is based on a patchwork of information- and data sources, which is common for all new fields (Snyder 2019). However, the TRL of the TMSR – 'early demonstration stage' – implies that all major conceptual issues are solved and only practical engineering issues remain, see (EPRI 2015). Essentially, there are no significant showstoppers. However, it is important to emphasize that the TRL approach is not an accurate approach and should be viewed as an indication, see (Héder 2017).

Since the LCOE approach forecasts the cost performance decades into the future, there are considerable uncertainties. However, these are relatively realistically handled by using Monte Carlo simulations. Furthermore, comparative cost analyses grounded in current LWR LCOE estimates as a reference point, reduce much of the uncertainty by focusing on the difference between the alternatives.

Additional research is needed, but this research suggests that the findings are unlikely to alter the conclusion. The public perception of nuclear power is probably the most challenging aspect, which is beyond the scope of this paper.

5. Concluding remarks

Nuclear energy is one of the key technologies going forward because it is virtually emission free and produces a huge amount of energy reliably. Unfortunately, there are public perception problems related to safety, waste management and costs, that were addressed in this paper. The fact that modern nuclear technology is a major improvement over older nuclear technologies is often ignored and the poor image of nuclear power perpetuates. Nuclear innovation is important, and emerging technology milestones must be more frequently communicated to the public. One such option is the TMSR, which although it dates is from the 1960s, has experienced a resurgence of interest to be considered as new technology today.

Based on the available literature, the paper presents a relatively coherent, comparative cost analysis between TMSR and LWR using LCOE as metric. Since the TMSR is still in the early demonstration stage, the uncertainties of the LCOE numbers are significant. Further research is required concerning both the technology itself, its performance and economic potential. However, given the conservatism of the presented LCOE analysis, it is unlikely to change the overall finding that TMSR concepts will provide clean, safe and cost-effective energy for sustainable development.

Acknowledgement

The author greatly acknowledges the detailed and the highly useful input provided by the two reviewers and the proofreading by Cecilia Haskins.

Notes

1. A breeder reactor is a nuclear reactor that generates more fissile material than it consumes. Breeder reactors achieve this because they generate enough neutrons to create more fissile fuel than they use, by irradiation of a fertile material, such as U-238 or Th-232 that is loaded into the reactor along with fissile fuel (Waltar and Reynolds 1981).
2. This information was downloaded 12 April 2020 from https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/plutonium.aspx
3. The ‘Red Book’ is the common term for the currently biennial report on world uranium resources, production and demand such as (OECD/NEA and IAEA 2008).
4. Accessed May 25, 2020, see https://www.newsweek.com/lost-chance-105291.
5. Transuranium elements are formed during irradiation of uranium fuel in a reactor and include elements such as neptunium, americium, and curium. These elements are present in the spent fuel in relatively small quantities compared to plutonium, and for that reason they are often also called minor actinides (MA) (Fanghänel et al. 2010).
6. Or the equivalent of the equivalent of 9000 full-power hours (during which the reactor was critical 80% of the time) when the reactor was fueled with U-235 and 2500 with U-233 fissile fuel (Delpech et al. 2009).
7. The Liquid Metal Fast Breeder Reactor (LMFBR) is a nuclear reactor that has been modified to increase the efficiency at which non-fissionable U-238 is converted to fissionable Pu-239, which can be used as fuel in the production of nuclear power, see https://www.encyclopedia.com/environment/encyclopedias-almanacs-transcripts-and-maps/liquid-metal-fast-breeder-reactor
8. In 2017, the world’s electricity consumption amounted to approximately 22,347 billion kilowatt hours, according to https://www.statista.com/.
9. A Liquid Metal Cooled Fast Reactor (LMCFR), Liquid Metal Fast Reactor (LMFR) or a Liquid Metal Fast Breeder Reactor (LMFBR) are advanced types of nuclear reactors where the primary coolant is liquid metal.
10. In the preconceptual 1000-MWe designs developed in the early 1970s, the liquid fuel salt typically enters the reactor vessel at 565°C and exits at 705°C and at approximately 1 atmosphere pressure (boiling point is approximately 1400°C) (Forsberg 2006).
11. Thorium-uranium extraction process developed at ORNL in the 1950s.

12. Some use Levelized Cost of Energy and others use Levelized Cost of Electricity.
13. The average OECD corporate tax rate is 23.3% in 2020, calculated with data accessed Janurayr 27, 2021 from https://stats.oecd.org/Index.aspx?DataSetCode=TABLE_II1
14. The Overnight Construction Cost (OCC) includes the costs of the direct engineering, procurement, and construction (EPC) services that the vendors and the architect-engineer team are contracted to provide, as well as the indirect owner's costs, which include land, site preparation, project management, training, contingencies and commissioning costs. The OCC excludes financing charges known as Interest During Construction. The OCC is the dominant cost because it is both the dominant component of life time costs for nuclear power, and the cost component that varies most over time and between countries (Lovering, Yip, and Nordhaus 2016).
15. Calculated from US EIA Inventory of Operating Generators as of July 2019 found on https://www.eia.gov.
16. Calculated using the https://www.usinflationcalculator.com/

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

Ade, B., A. Worrall, J. Powers, S. Bowman, G. Flanagan, and J. Gehin. 2014. *Safety and Regulatory Issues of the Thorium Fuel Cycle*. Oak Ridge, TN: U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Oak Ridge National Laboratory.

Allibert, M., M. Aufiero, M. Brovchenko, S. Delpech, V. Ghetta, D. Heuer, A. Laureau, and E. Merle-Lucotte. 2016. "Molten Salt Fast Reactors." In *Handbook of Generation IV Nuclear Reactors*, edited by I. L. Pioro, 157–188. Cambridge: Woodhead Publishing.

ANL. 2018. *Pyroprocessing Technologies: Recycling Used Nuclear Fuel for a Sustainable Energy Future*. Lemont, IL: US Department of Energy, Argonne National Laboratory (ANL). https://www.anl.gov/sites/www/files/2018-2010/Pyroprocessing_brochure_2018.pdf.

Arnott, R. D. 2003. "Dividends and the Three Dwarfs." *Financial Analysts Journal* 59 (2): 4–6.

Ault, T., B. van Gosen, S. Krahn, and A. Croff. 2016. "Natural Thorium Resources and Recovery: Options and Impacts." *Nuclear Technology* 194 (May): 136–151.

Bauer, S. 2018. *Seawater Yields First Grams of Yellowcake*. Seqium, WA: Pacific Northwest National Laboratory.

Bernstein, P. L. 1976. "The Time of Your Life." *The Journal of Portfolio Management* 2 (4): 4.

Berthélemy, M., and L. Escobar Rangel. 2015. "Nuclear Reactors' Construction Costs: The Role of Lead-Time, Standardization and Technological Progress." *Energy Policy* 82 (July): 118–130.

Chang, K. 2002. "Alvin Radkowsky, 86, Developer of a Safer Nuclear Reactor Fuel." *The New York Times*. March 5th, Section C.

Cochran, J. K., A. E. Carey, E. R. Sholkovitz, and L. D. Surprenant. 1986. "The Geochemistry of Uranium and Thorium in Coastal Marine Sediments and Sediment Pore Waters." *Geochimica et Cosmochimica Acta* 50: 663–680.

Cohen, B. L. 1983. "Breeder Reactors: A Renewable Energy Source." *American Journal of Physics* 51 (1): 75–76.

Conca, J. 2016. *Uranium Seawater Extraction Makes Nuclear Power Completely Renewable Forbes*. Jersey City, NJ. https://www.forbes.com/sites/jamesconca/2016/2007/2001/uranium-seawater-extraction-makes-nuclear-power-completely-renewable/.

Darling, S. B., F. You, T. Veselkad, and A. Velos. 2011. "Assumptions and the Levelized Cost of Energy for Photovoltaics." *Energy & Environmmental Science* 4 (9): 3077–3704.

David, S., E. Huffer, and H. Nifenecker. 2007. "Revisiting the Thorium-Uranium Nuclear Fuel Cycle." *EuroPhysicsNews* 38 (2): 24–27.

Delene, J. G. 1994. "Advanced Fission and Fossil Plant Economics-implications for Fusion." *Fusion Technology* 26 (3, Part II): 1105–1110.

Delene, J. G., J. Sheffield, K. A. Williams, R. L. Reid, and S. W. Hadley. 1999. *An Assessment of the Economics of Future Electric Power Generation Options and the Implications for Fusion*. Oak Ridge, TN: Oak Ridge National Laboratory (ORNL).

Delpech, S., E. Merle-Lucotte, D. Heuer, M. A. Allibert, V. Ghetta, C. Le-Brun, X. Doligez, and G. S. Picard. 2009. "Reactor Physic and Reprocessing Scheme for Innovative Molten Salt Reactor System." *Journal of Fluorine Chemistry* 130 (1): 11–17.

Dimson, E., P. Marsh, and M. Staunton. 2008. "Chapter 11 – The Worldwide Equity Premium: A Smaller Puzzle." In *Handbook of the Equity Risk Premium*, edited by R. Mehra, 467–514. Amsterdam: Elsevier.

Doemeland, D., and J. Trevino. 2014. *Which World Bank Reports Are Widely Read? Policy Research Working Paper*. Washington, DC: World Bank, Development Economics Vice Presidency, Operations and Strategy Unit, Group no. WPS6851.

Emblemsvåg, J. 2003. *Life-cycle Costing: Using Activity-based Costing and Monte Carlo Methods to Manage Future Costs and Risks*. Hoboken, NJ: John Wiley & Sons.

Emblemsvåg, J. 2020. "On the Levelised Cost of Energy of Windfarms." *International Journal of Sustainable Energy* 39 (7): 700–718.

Emblemsvåg, J. 2021a. "On the Levelized Cost of Energy of Solar Photovoltaics." *International Journal of Sustainable Energy* 40. doi: 10.1080/14786451.2020.1867139.

Emblemsvåg, J. 2021b. "How Thorium-based Molten Salt Reactors Can Provide Clean, Safe, and Cost-effective Technology for Deep-sea Shipping." *Marine Technology Society Journal* 55 (1): 56–72.

EMWG. 2007. Cost Estimating Guidelines for Generation IV Nuclear Energy Systems (GIF/EMWG/2007/004). Geneva, Generation IV International Forum, Economic Modeling Working Group (EMWG).

Engel, J. R., H. F. Bauman, J. F. Dearing, W. R. Grimes, E. H. McCoy, and W. A. Rhoades. 1980. *Conceptual Design Characteristics of a Denatured Molten-Salt Reactor with Once-through Fueling*. Oak Ridge, TN: Oak Ridge National Laboratory.

EPRI. 2015. *Program on Technology Innovation: Technology Assessment of a Molten Salt Reactor Design*. Palo Alto, CA: Electric Power Research Institute (EPRI).

Estrada, J. 2014. "Stocks, Bonds, Risk, and the Holding Period: An International Perspective." *The Journal of Wealth Management* 16 (2): 25–44.

Fanghänel, T., J.-P. Glatz, R. J. M. Konings, V. V. Rondinella, and J. Somers. 2010. "Transuranium Elements in the Nuclear Fuel Cycle." In *Handbook of Nuclear Engineering*, edited by D. G. Cacuci, 2935–2998. Boston, MA: Springer.

Forsberg, C. W. 2006. *Molten-Salt-Reactor Technology Gaps. 2006 International Congress on the Advances in Nuclear Power Plants*. Reno, NV: American Nuclear Society.

Furukawa, Kazuo, Kazuto Arakawa, L. Berrin Erbay, Yasuhiko Ito, Yoshio Kato, Hanna Kiyavitskaya, Alfred Lecocq, et al. 2008. "A Road Map for the Realization of Global-scale Thorium Breeding Fuel Cycle by Single Molten-Fluoride Flow." *Energy Conversion and Management* 49: 1832–1848.

Furukawa, K., H. Numata, Y. Kato, K. Mitachi, R. Yoshioka, A. Furuhashi, Y. Sato, and K. Arakawa. 2005. "New Primary Energy Source by Thorium Molten-Salt Reactor Technology." *Electrochemistry* 73 (8): 552–563.

Gormley, R., J. Sinkiewicz, and B. Wolfe. 2020. *License Renewals Could Modernize U.S. Nuclear; Supply Base Will Need to Keep Pace: Power Magazine*. Rockville, MD. https://www.powermag.com/license-renewals-could-modernize-u-s-nuclear-supply-base-will-need-to-keep-pace/

Greaves, E. D., K. Furukawa, L. Sajo-Bohus, and H. Barros. 2012. "The Case for the Thorium Molten Salt Reactor." *AIP Conference Proceedings* 1423 (453). doi.org/10.1063/1.3688845.

Hargraves, R. 2012. *Thorium: Energy Cheaper Than Coal*. Scotts Valley, CA: CreateSpace Independent Publishing Platform, Amazon.

Hargraves, R., and R. Moir. 2010. "Liquid Fluoride Thorium Reactors: An Old Idea in Nuclear Power Gets Reexamined." *American Scientist* 98 (July-August): 304–313.

Haubenreich, P. N., and J. R. Engel. 1970. "Experience with the Molten-salt Reactor Experiment." *Nuclear Applications and Technology* 8 (2): 118–136.

Héder, M. 2017. "From NASA to EU: The Evolution of the TRL Scale in Public Sector Innovation." *The Innovation Journal: The Public Sector Innovation Journal* 22 (2): Paper no. 3.

Hollenbach, D. F., and J. M. Herndon. 2001. "Deep-earth Reactor: Nuclear Fission, Helium, and the Geomagnetic Field." *Proceedings of the National Academy of Sciences* 98 (20): 11085–11090.

Huh, C.-A., W. S. Moore, and David C. Kadko. 1989. "Oceanic 232Th: A Reconnaissance and Implications of Global Distribution from Manganese Nodules." *Geochimica et Cosmochimica Acta* 53: 1357–1366.

IAEA. 2005. *Thorium Fuel Cycle — Potential Benefits and Challenges. IAEA Nuclear Energy Series*. Wien: International Atomic Energy Agency (IAEA), Nuclear Fuel Cycle and Materials Section.

IAEA. 2018. *Status and Trends in Spent Fuel and Radioactive Waste Management. IAEA Nuclear Energy Series*. Wien: International Atomic Energy Agency (IAEA).

IAEA. 2019. *Nuclear Power Reactors in the World*. Vienna: International Atomic Energy Agency.

IAEA. 2020. *Advances in Small Modular Reactor Technology Developments – A Supplement to: IAEA Advanced Reactors Information System (ARIS).IAEA Nuclear Energy Series*. Wien: International Atomic Energy Agency (IAEA), Department of Nuclear Energy, Nuclear Power Technology Development Section (NPTDS).

IPCC. 2014. *Climate Change 2014 Mitigation of Climate Change: Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. New York: Cambridge University Press.

IRENA. 2012. *Renewable Energy Technologies: Cost Analysis Series*. Abu Dhabi: United Arab Emirates,International Renewable Energy Agency (IRENA), IRENA Innovation and Technology Centre.

Jarvis, S., O. Deschenes, and A. Jha. 2019. *The Private and External Costs of Germany's Nuclear Phase-Out*. Cambridge, MA: National Bureau of Economic Research (NBER).

Jiang, M., H. Xu, and Z. Dai. 2012. "Advanced Fission Energy Program-TMSR Nuclear Energy System." *Bulletin of Chinese Academy of Sciences* 27: 366–374.

Juhasz, A. J., R. A. Rarick, and R. Rangarajan. 2009. *High Efficiency Nuclear Power Plants Using Liquid Fluoride Thorium Reactor Technology: NASA Scientific and Technical Information (STI)*. Cleveland, OH: National Aeronautics and Space Administration (NASA), Glenn Research Center.

Kamei, T. 2011. "Implementation Strategy of Thorium Nuclear Power in the Context of Global Warming." In *Nuclear Power: Deployment, Operation and Sustainability*, edited by P. Tsvetkov, 365–382. Rijeka: InTech.

Kazimi, M. S. 2004. "Thorium Fuel for Nuclear Energy." *American Scientist* 91 (September–October): 408–415.

Knight, S. 2008. "New power generation." *Financial Times*.

LANL. 2009. *Plutonium Processing at Los Alamos. Actinide Research Quarterly*. Los Alamos: Los Alamos National Laboratory (LANL).

LeBlanc, D. 2010. "Molten Salt Reactors: A New Beginning for an Old Idea." *Nuclear Engineering and Design* 240 (6): 1644–1656.

Lovering, J. R., A. Yip, and T. Nordhaus. 2016. "Historical Construction Costs of Global Nuclear Power Reactors." *Energy Policy* 91 (April): 371–382.

MacPherson, H. G. 1985. "The Molten Salt Reactor Adventure." *Nuclear Science and Engineering* 90: 374–380.

Markandya, A., and P. Wilkinson. 2007. "Electricity Generation and Health." *The Lancet* 370 (9591): 979–990.

Martin, R. 2009. "Utanium Is so Last Century – Enter Thorium, the New Green Nuke." *Wired Magazine*.

Martin, R. 2012. *Super Fuel: Thorium, the Green Energy Source for the Future*. New York: Plagrave Macmillan.

Mathieu, L., D. Heuer, R. Brissot, C. Garzenne, C. Le Brun, D. Lecarpentier, E. Liatard, et al. 2006. "The Thorium Molten Salt Reactor: Moving on from the MSBR." *Progress in Nuclear Energy* 48: 664–679.

Mignacca, B., and G. Locatelli. 2020. "Economics and Finance of Molten Salt Reactors." *Progress in Nuclear Energy* 129. doi:10.1016/j.pnucene.2020.103503.

MIT. 2003. *The Future of Nuclear Power – An Interdisciplinary MIT Study*. Boston, MA: Massachusetts Institute of Technology.

MIT. 2009. *Update of the MIT 2003 The Future of Nuclear Power – An Interdisciplinary MIT Study*. Boston, MA: Massachusetts Institute of Technology.

MIT. 2018. *The Future of Nuclear Energy in a Carbon-Constrained World – An Interdisciplinary MIT Study*. Boston, MA: Massachusetts Institute of Technology.

Moir, R. W. 2002. "The Cost of Electricity from Molten Salt Reactors (MSR)." *Nuclear Technology* 138 (1): 93–95.

Moir, R. W., and E. Teller. 2005. "Thorium-fueled Underground Power Plant Based on Molten Salt Technology." *Nuclear Technology* 151 (September): 334–340.

National Audit Office. 2017. *Hinkley Point C*. London: National Audit Office, Department for Business, Energy & Industrial Strategy.

Nozaki, Y., and Y. Horibe. 1983. "Alpha-emitting Thorium Isotopes in Northwest Pacific Deep Waters." *Earth and Planetary Science Letters* 65: 39–50.

NRC. 2021a. *Three Mile Island Accident. Backgrounder*. Washington, DC: United States Nuclear Regulatory Commission (NRC).

NRC. 2021b. *Fermi – Unit 1*. Washington, DC: United States Nuclear Regulatory Commission (NRC). https://www.nrc.gov/info-finder/decommissioning/power-reactor/enrico-fermi-atomic-power-plant-unit-1.html.

OECD/NEA. 2012. *Nuclear Energy Today*. Paris: Organization for Economic Cooperation and Development (OECD), Nuclear Energy Agency.

OECD/NEA. 2015. *Introduction of Thorium in the Nuclear Fuel Cycle; Short- to Long-term Considerations*. Paris: Organization for Economic Cooperation and Development (OECD), Nuclear Energy Agency.

OECD/NEA and IAEA. 2008. *Uranium 2008: Resources, Production and Demand (Red Book): A Joint Report by the OECD Nuclear Energy Agency and the International Atomic Energy Agency*. Paris: Organization for Economic Cooperation and Development (OECD), Nuclear Energy Agency (NEA) and the International Atomic Energy Agency (IAEA).

OECD/NEA and IAEA. 2014. *Uranium 2014: Resources, Production and Demand (Red Book): A Joint Report by the OECD Nuclear Energy Agency and the International Atomic Energy Agency*. Paris: Organization for Economic Cooperation and Development (OECD), Nuclear Energy Agency (NEA) and the International Atomic Energy Agency (IAEA).

Olsson, L. E. 1994. "Energy-meteorology: A New Discipline." *Renewable Energy* 5 (Part II): 1243–1246.

Ontario Power Authority. 2008. *Facilitating the Development and Use of Renewable Energy and Enabling 2010 and 2025 Renewable Targets*. Toronto: Ontario Power Authority (OPA).

ORNL. 2012. *Categorization of Used Nuclear Fuel Inventory in Support of a Comprehensive National Nuclear Fuel Cycle Strategy*. Oak Ridge, TN: Oak Ridge National Laboratory (ORNL).

Peterson, P. F. 2003. "Multiple-Reheat Brayton Cycles for Nuclear Power Conversion with Molten Coolants." *Nuclear Technology* 144 (3): 279–288.

Pioro, I. L. 2016. *Handbook of Generation IV Nuclear Reactors.Woodhead Publishing Series in Energy*. Cambridge: Woodhead Publishing.

Radkowsky, A. 1984. "The Thorium Nuclear Power's Future." *The New York Times*. May 15th, Section A.

Radkowsky, A., and A. Galperin. 1998. “The Nonproliferative Light Water Thorium Reactor: A New Approach to Light Water Reactor Core Technology.” *Nuclear Technology* 124 (3): 215–222.

Reichenberg, L., F. Hedemus, M. Odenberger, and F. Johnsson. 2018. “The Marginal System LCOE of Variable Renewables – Evaluating High Penetration Levels of Wind and Solar in Europe.” *Energy* 152: 914–924.

Robertson, R. C. 1971. *Conceptual Design Study of a Single-fluid Molten-salt Breeder Reactor*. Oak Ridge, TN: U.S. Atomic Energy Commission, Oak Ridge National Laboratory (ORNL).

Robertson, R. C., O. L. Smith, R. B. Briggs, and E. S. Bettis. 1970. *Two-fluid Molten-salt Breeder Reactor Design Study*. Oak Ridge, TN: U.S. Atomic Energy Commission, Oak Ridge National Laboratory (ORNL).

Rodriguez, P., and C. V. Sundaram. 1981. “Nuclear and Materials Aspects of the Thorium Fuel Cycle.” *Journal of Nuclear Materials* 100 (1–3): 227–249.

Rogelj, J., D. Shindell, K. Jiang, S. Fifita, P. Forster, V. Ginzburg, C. Handa, et al. 2018. “Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. Global Warming of 1.5°C.” In *An IPCC Special Report on the Impacts of Global Warming of 1.5°C Above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, edited by Valérie Masson-Delmotte, Panmao Zhai, Hans-Otto Pörtner, Debra Roberts, Jim Skea, Priyadarshi R. Shukla, Anna Pirani, etal, 93–174. Geneva: IPCC/WMO.

Rosenthal, M. W. 2009. *An Account of Oak Ridge National Laboratory’s Thirteen Nuclear Reactors*. Oak Ridge, TN: Oak Ridge National Laboratory (ORNL).

Rubbia, C. 2013. *A Future for Thorium Power? The Thorium Energy Conference 2013*. Geneva: CERN.

Rubbia, C., et al. 2016. “A Future for Thorium Power? Thorium Energy for the World: Proceedings of the ThEC13 Conference.” In *CERN, Globe of Science and Innovation, Geneva*, edited by J.-P. Revol and M. Bourquin, 9–25. Geneva: Springer.

Schaffer, M. B. 2013. “Abundant Thorium as an Alternative Nuclear Fuel: Important Waste Disposal and Weapon Proliferation Advantages.” *Energy Policy* 60 (September): 4–12.

Siemer, D. D. 2015. “Why the Molten Salt Fast Reactor (MSFR) is the ‘Best’ Gen IV Reactor.” *Energy Science & Engineering* 3 (2): 83–97.

Snyder, H. 2019. “Literature Review as a Research Methodology: An Overview and Guidelines.” *Journal of Business Research* 104 (November): 333–339.

Sovacool, B. K., R. Andersen, S. Sorensen, K. Sorensen, V. Tienda, A. Vainorius, O. M. Schirach, and F. Bjørn-Thygesen. 2016. “Balancing Safety with Sustainability: Assessing the Risk of Accidents for Modern Low-carbon Energy Systems.” *Journal of Cleaner Production* 112 (5): 3952–3965.

Tsouris, C. 2017. “Uranium Extraction: Fuel from Seawater.” *Nature Energy* 2. doi: 10.1038/nenergy.2017.22.

Ueckerdt, F., L. Hirth, G. Luderer, and O. Edenhofer. 2013. “System LCOE: What Are the Costs of Variable Renewables?” *Energy* 63: 61–75.

US EIA. 2019a. *Electric Power Annual 2019*. Washington, DC: US Energy Information Administration.

US EIA. 2019b. *Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2019*. Washington, DC: US Energy Information Administration.

Vijayan, P. K. 2013. *Overview of Thorium Programme in India. Thorium Energy for the World. Proceedings of the ThEC13 Conference, October 27-31, 2013*. Geneva: CERN.

Waltar, A. E., and A. B. Reynolds. 1981. *Fast Breeder Reactors*. New York: Pergamon Press.

Weinberg, A. M. 1997. “The Proto-History of the Molten Salt System.” *Journal of Acceleration Plasma Research* 2: 22–26.

Weinberg, A. M., and R. P. Hammond. 1970. “Limits to the Use of Energy.” *American Scientist* 58 (4): 412–418.

World Nuclear Association. 2011. *Nuclear Power Reactor Characteristics.WNA Pocket Guide*. London: World Nuclear Association.

World Nuclear Association. 2019. *Economics of Nuclear Power*. London: World Nuclear Association.

World Nuclear Association. 2020. *Molten Salt Reactors*. London: World Nuclear Association. https://www.world-nuclear.org/information-library/current-and-future-generation/molten-salt-reactors.aspx.

World Nuclear Association. 2021. *Fukushima: Background on Reactors*. London: World Nuclear Association.

Wu, J., J. Chen, X. Kang, X. Li, C. Yu, C. Zou, and X. Cai. 2019. “A Novel Concept for a Molten Salt Reactor Moderated by Heavy Water.” *Annals of Nuclear Energy* 132: 391–403.

Zou, C. Y., C. Z. Cai, C. G. Yu, J. H. Wu, and J. G. Chen. 2018. “Transition to Thorium Fuel Cycle for TMSR.” *Nuclear Engineering and Design* 330: 420–428.