Progress in Nuclear Energy 129 (2020) 103503

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: http://www.elsevier.com/locate/pnucene

Economics and finance of Molten Salt Reactors

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ARTICLE INFO

Keywords:
Molten salt reactor
Economics
Finance
LCOE
Modularisation
GEN IV reactor

ABSTRACT

There is a long-standing and growing interest in Molten Salt Reactors (MSRs) mainly because of their potential advantages in terms of safety, sustainable fuel cycle, and the high melting and boiling points of salt which allow operations at high temperatures and atmospheric pressure with potential merits in terms of cost. A key objective of MSRs is to have a life-cycle cost advantage over other energy sources. Leveraging a systematic literature review, this paper firstly provides an overview of "*what we know*" about MSR economics and finance following two main streams: scientific and industrial literature. Secondly, this paper highlights "*what we should know*" about the economics and finance of MSRs, suggesting a research agenda. The literature is very scarce and focuses on MSR overnight capital cost estimations and the comparison between MSR cost of electricity and other energy sources. Cost estimations need to be more transparent and independently assessed. Furthermore, there is no peer-reviewed literature on MSR financing, only claims from vendors.

1. Introduction

The evolution of Nuclear Power Plants (NPPs) is usually divided into four generations (GIF, 2014):

- I generation (1950–1970): early prototypes to test different technologies[1];
- II generation (1970–1995): medium-large commercial NPPs, mostly Light Water Reactors (LWRs), conceived to be reliable and economically competitive;
- III/III + generation (1995–2030): mostly an evolution of the II generation LWR;
- IV generation (2030+): designs called "revolutionaries" because of their discontinuity with the III/III + generation NPPs.
  The Generation IV International Forum (GIF) lists six GEN IV technologies (GIF, 2014):
- VHTR (Very-High-Temperature Reactor) is a thermal reactor technology cooled by helium in the gaseous phase and moderated by graphite in the solid phase;
- SFR (Sodium-cooled Fast Reactor) is a fast reactor technology cooled by sodium in the liquid phase. It is the most investigated fast reactor;
- SCWR (Supercritical-Water-cooled Reactor) is a thermal/fast reactor technology cooled by supercritical water. It is considered as an evolution of the actual boiling water reactor because of its comparable plant layout and size, same coolant and identical main application, i.e. electricity production;
- GFR (Gas-cooled Fast Reactor) is a fast reactor technology cooled by helium in the gaseous phase. This technology aims to put together a high-temperature reactor with a fast spectrum core;
- LFR (Lead-cooled Fast Reactor) is a fast reactor technology cooled by lead or lead-bismuth eutectic. It is a liquid metal reactor (similar to SFR) for electricity production and actinides management;
- MSR (Molten Salt Reactor) is a fast or thermal reactor technology cooled by molten salts in the liquid phase and moderated, in most cases, by the graphite. In this technology, the fuel can be in either liquid or solid form (Zheng et al., 2018).

Currently, there is an increasing interest in MSRs both from industry and academia. (Zheng et al., 2018) summarise the advantages of MSRs. The high melting and boiling points of salt allow operating at high temperatures (increasing the efficiency in electricity generation) and atmospheric pressure (lowering the risk of a significant break and loss of coolant because of an accident). In addition, the opportunity to dissolve

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[1] It is worth clarifying the difference between technology, design, and project right at the start of the paper with an example. An example of technology is the Pressurised Water Reactors (PWR), which has several designs. An example of PWR design is the AP1000. A project implementing the AP1000 is the HAIYANG 1 in China. Therefore, for each technology there are several designs, and for each design there could be different projects around the world.

https://doi.org/10.1016/j.pnucene.2020.103503
Received 18 February 2020; Received in revised form 17 August 2020; Accepted 1 September 2020
Available online 19 September 2020

fuel materials in the salt eliminates the fabrication and disposal of solid fuel. Furthermore, the opportunity to constantly remove fission products from the liquid fuel allows a higher fuel burnup and less decay heat is generated after reactor shutdown. MSRs are also characterised by a passive shutdown ability, low-pressure piping, negative void reactivity coefficient and chemically stable coolant (Saraf et al., 2018; Zheng et al., 2018). MSRs can be designed as nuclear waste "burners" or "breeders". In the case of "burners", MSRs have the potential to reduce nuclear waste. In the case of "breeders", MSRs could greatly extend nuclear fuel resources (IAEA, 2020a; Zhou et al., 2020).

Given their attractive features, the interest in MSRs is not new. Indeed, from the 1950s to 2020, many MSR concepts and designs have been proposed using different fission fuels (i.e. Uranium, Plutonium or Thorium) and salt compositions (e.g. chlorides, fluorides) (IAEA, 2020a; Serp et al., 2014). In the 1960s and 1970s, the Oak Ridge National Laboratory (ORNL) demonstrated many aspects of the MSR technology with the MSR Experiment, where the MSR ran for a relatively long period of time (15 months), and maintenance was carried out safely and without substantial issues (Macpherson, 1985; Oak Ridge National Laboratory, 2010; Serp et al., 2014).

However, although there is a long-standing and growing interest in MSRs, there are no MSRs in commercial operation, under construction or planned for near term commercial operation (IAEA, 2019). Therefore, while the vast majority of MSRs literature focuses on technical aspects, there is little historical data about the economics or financing of MSR projects (Serp et al., 2014; Wang et al., 2020; Wooten and Fratoni, 2020; Zeng et al., 2020; Zhou et al., 2020; Zhuang et al., 2020).

Information about MSR economics and finance is scattered between a few academic papers, not peer-reviewed publications and vendor websites. This paper aims to provide, through a Systematic Literature Review (SLR), a summary of "*what we know*" and "*what we should know*" about the economics and finance of MSRs. Instead of a traditional narrative review, an SLR has been performed to provide a holistic perspective and allow repeatability. The research objective is "to critically summarise the state-of-the-art about MSR economics and finance and the most relevant gaps in knowledge".

The rest of the paper is structured as follows. Section 2 introduces key economic and financial concepts; Section 3 presents the methodology used to conduct the SLR; Section 4 summarises "*what we know*" about MSR economics and finance; Section 5 summarises "*what we should know*" suggesting a research agenda; Section 6 concludes the paper.

2. Economic and financial concepts

Considering this paper deals with the economics and finance of MSRs, it is worth clarifying the difference between economics and finance. Economics is the study of the management of goods and services, comprising production, consumption, and the elements affecting them (Ehrhardt, 2011; Investopedia, 2019a). Economic studies deal with cost estimations (e.g. construction cost, decommissioning cost), identification of cost drivers (e.g. size, construction technique), etc. Usually, economic models do not consider the payment of taxes, remuneration of debt or equity, or debt amortisation captured by financial analysis (Ehrhardt, 2011). Finance focuses on cash flows or equivalent means. For instance, asking "how much is the construction cost of an MSR?" is an economic question, while asking "who will pay to build an MSR?" is a financial question. The next sections provide an overview of the main economic and financial concepts enabling the reader to understand the following sections of the paper.

2.1. Cost vs price

Commonly misunderstood are the terms cost and price. The cost is the sum of the expenses for a company to manufacture a product (e.g. an MSR) or to provide a service (e.g. maintenance). The price is the amount the customer (e.g. the utility) pays for a product or service, and it is usually market-driven. Therefore, the cost is an endogenous measure (dependent on technology, design, etc.), while the price is an exogenous measure (dependent on the market, policy decisions, etc.). Price can be less than cost if, for example, the vendors aim to build a reference plant to gain experience (and not directly profiting from it) or to make a profit from selling additional services (e.g. maintenance) or products (e.g. fuel).

2.2. Top-down vs bottom-up approach

There are two main cost estimation approaches: top-down and bottom-up. Following the top-down approach, a new project is compared to similar projects already completed (Trendowicz and Jeffery, 2014), and the cost of a project is estimated by increasing or decreasing the cost items (e.g. material, equipment, systems) of similar projects. The top-down approach is preferred when there is a lack of information (GIF/EMWG, 2007). Conversely, following the bottom-up approach, the cost of a project is estimated as the sum of the costs of each element (e.g. a pump), material (e.g. kg of concrete), labour (e.g. the number of hours worked by certain type of workers), service (e.g. site security), etc. The bottom-up approach is most suitable for projects with a detailed design, a specific site for the construction and availability of detailed data (GIF/EMWG, 2007). (GIF/EMWG, 2007) provides guidelines on both top-down and bottom-up cost estimation approaches for Gen IV reactors.

2.3. General cost items

- Direct costs: All costs to build an NPP apart from support services (e.g. field indirect costs, construction supervision) and other indirect costs (e.g. design services) (GIF/EMWG, 2007). For instance, (MIT, 2018) includes, among others, the following direct costs in the MSR cost estimation (summarised in Section 4.1): costs for reactor and turbine plant equipment; labour costs for installation; and civil work costs to prepare the site.
- Indirect costs: Design services, construction supervision, and all the costs not directly associated with the construction of an NPP (GIF/EMWG, 2007). For instance, (MIT, 2018) includes, among others, the following indirect costs in the MSR cost estimation (summarised in Section 4.1): costs for construction management; procurement; quality inspections; project fees; and taxes.
- Base costs: The initial NPP cost estimation before validation and any cost adjustments (GIF/EMWG, 2007).
- Base construction cost: The most likely NPP construction cost, considering only direct and indirect costs (GIF/EMWG, 2007).
- Contingency: An addition to account for uncertainty in NPP cost estimation (GIF/EMWG, 2007).

2.4. Generation costs of a nuclear power plant

In the nuclear sector, the generation costs (or life-cycle costs) are commonly divided into four groups: capital cost; operation and maintenance costs; fuel cost; and decommissioning cost.

- Capital cost is the sum of the "overnight capital cost" and Interest During Construction (IDC) (MIT, 2018). (GIF/EMWG, 2007) defines the "overnight capital cost" as "*the base construction cost plus applicable owner's cost, contingency, and first core costs*" (Page 25). Therefore, the time value costs (e.g. Interest During Construction) are not included. Examples of owner's costs are land, site works, switchyards, project management, administration and associated buildings (World Nuclear Association, 2008). The "overnight capital cost" is also defined as "overnight cost".
- Operation and Maintenance (O&M) costs are the costs to maintain and operate an NPP, i.e. all the non-fuel costs, such as plant staffing, purchased services, replaceable operating materials (e.g. worn

parts), and equipment. O&M costs can be divided into fixed and variable. Fixed O&M costs do not depend on the power generation level, e.g. plant staffing. Variable O&M costs depend on electricity production, e.g. non-fuel consumables (GIF/EMWG, 2007). The fixed costs represent by far the biggest percentage of O&M costs.

- Fuel cost is the sum of all activities related to the nuclear fuel cycle, from mining the uranium ore to the final high-level waste disposal (NEA, 1994). Enrichment of uranium, manufacture of nuclear fuel, reprocessing of spent fuel, and any associated research are examples of activities related to the nuclear fuel cycle (IAEA, 2006).
- Decommissioning cost includes all the costs from the planning for decommissioning until the final remediation of the site. Therefore, the costs in the transition phase from the shutdown to decommissioning and the costs to perform the decontamination, dismantling and management of the waste are included (IAEA, 2013; Invernizzi et al., 2020b, 2019a; 2017; Locatelli and Mancini, 2010).

2.5. Indicators of the economic and financial performance of a power plant

- Levelised Cost of Electricity and Levelised Avoided Cost of Electricity

One of the most relevant indicators for policy-makers is the levelised cost of the electricity produced by the power plant. This indicator, usually termed "Levelised Unit Electricity Cost" (LUEC) or "Levelised Cost Of Electricity" (LCOE) accounts for all the life cycle costs, and it is expressed in terms of energy currency, usually as [$/kWh] (IAEA, 2018). In the nuclear sector, the main component of the LCOE is the capital cost (50–75%), followed by O&M and fuel cost (Carelli and Ingersoll, 2014). From a policy perspective, a power plant is considered economically attractive when its projected LCOE is lower than its projected Levelised Avoided Cost of Electricity (LACE). LACE is the power plant's value to the grid (EIA, 2019). In other words, according to (EIA, 2015), LACE "*reflects the cost that would be incurred to provide the same supply to the system if new capacity using that specific technology was not added*". LACE is usually expressed as [$/kWh]. LCOE and LACE are extremely relevant for policy-makers and the appraisal of the design in its early stages. However, coming close to construction, the following parameters are also relevant.

- Net Present Value and Internal Rate of Return

Two of the most relevant indicators for utility companies (or investors in general) to assess the profitability of investing in a power plant are the Net Present Value (NPV) and the Internal Rate of Return (IRR) (Locatelli et al., 2014; Locatelli and Mancini, 2011; Mignacca and Locatelli, 2020). The NPV uses a discount factor to weight "present cost" versus the "future revenue" and measures the absolute profitability in terms of currency (Investopedia, 2019b). The discount factor depends on the source of financing and applied in practice as the Weighted Average Cost of Capital (WACC). A high WACC gives more weight to present cost with respect to future revenue (promoting low capital technologies such as gas plants). A low WACC gives similar weighting to present cost and future revenues (promoting capital-intensive technologies such as NPPs). The IRR is a specific dimensionless indicator, i.e. the value of WACC that brings the NPV to zero. The greater the IRR, the higher is the profitability of the investment as a percentage on the money invested (Investopedia, 2019c; Locatelli et al., 2014).

2.6. Potential approaches for cost reduction

This section provides an overview of three key approaches to reduce the costs of NPPs.

2.6.1. The economy of scale

Historically, the size of NPPs has increased from a few hundred MWe to 1500 MWe and more. The reason behind increasing the size of NPPs is the economy of scale principle, i.e. 'bigger is cheaper'. According to the economy of scale principle, the capital cost [currency/kWe] and LCOE [currency/MWh] of an NPP decreases when size increases. The capital cost reduction is due to several factors such as: the rate reduction of unique set-up costs (e.g. siting activities, work to access the transmission network); the higher performance of larger equipment (e.g. steam generator, pumps); and the more efficient use of raw material (Locatelli et al., 2014). However, the implementation of the economy of scale principle can present drawbacks. For instance, other things being equal, the larger the reactor size, the higher is the up-front investment and problems of affordability for the utility companies. Furthermore, grid connection could struggle to reliably handle increased power (Black et al., 2015; OECD/NEA, 2011). These and other factors, such as economy of multiples and enhanced modularisation, are driving the growing interest in Small Modular nuclear Reactors (SMRs) (Mignacca and Locatelli, 2020).

2.6.2. The economy of multiples

NPP life-cycle costs (construction, operations, decommissioning) depend on how many identical (or at least very similar) units are built in the same site, country or globally. When the same identical plant is delivered more than once (ideally several times by the same organisations), the economy of multiples is achieved reducing, other things being equal, the unitary investment cost (Boarin et al., 2012; Locatelli and Mancini, 2012a; Mignacca and Locatelli, 2020). The economy of multiples in the construction of NPPs is related to the idea of "mass production", firstly adopted in the automotive industry and later in other fields (e.g. aerospace, production of computers and smartphone). The economy of multiples is achieved because of two key factors: the learning process and the co-siting economies (Locatelli, 2018).

- Learning process

The replicated supply of plant components and the replicated construction and operation of the plant determine the learning economies. The learning process reduces the cost of equipment, material and work (Locatelli, 2018) and reduces the construction schedule (EY, 2016; Mignacca and Locatelli, 2020). As shown in (Locatelli et al., 2014), the construction schedule is a critical economic and financial aspect of an NPP for two main reasons:

1. Fixed daily cost. On an NPP construction site, there are thousands of people working, often utilising expensive equipment. Consequently, each working day has relevant fixed costs.
2. The postponing of cash in-flow. Postponing the cash in-flow has two main negative effects. First, each extra-year of construction increases the interest to be paid on the debt. Second, the present value of future cash flow decreases exponentially with time.

Therefore, the unit cost of a First-of-A-Kind (FOAK) MSR is expected to be higher than the unit cost of an Nth-of-A-Kind (NOAK) MSR. The consequences of the learning process should be considered at two levels:

1) World-level – After the FOAK MSR for commercial operation in the world, a cost reduction for the NOAK MSR is expected even if they are built in different countries.
2) Country-level – If a country plans to build a series of MSRs for commercial operation, there is a learning process from the FOAK to the NOAK MSR stronger than the "world-level" because of the same regulatory regime and similar (or identical) supply chain.

- Co-siting economies

Co-siting economies result from the set-up activities related to siting (e.g. acquisition of land rights, connection to the transmission network) which have already been carried out, and by certain fixed indivisible costs which can be saved when installing the second and subsequent units (Locatelli, 2017). Therefore, the larger the number of co-sited units, the lower the total investment cost for each unit (Carelli et al., 2008, 2007). Operational costs across MSRs would also be reduced because of sharing of personnel and spare parts across multiple units (Carelli et al., 2007) or the possibility to share the cost of upgrades, e.g. the cost of upgrading software (Locatelli, 2018). (IAEA, 2005) suggests that identical units at the same site cost on average 15% less than a single unit. Siting and licensing costs, site labour and common facilities mostly drive such cost reduction. Therefore, two identical MSRs at the same site are envisaged to cost less than doubling the cost of a single MSR.

2.6.3. Modularisation

Modularisation is a construction strategy characterised by the factory fabrication of modules for shipment and installation on-site as complete assemblies (GIF/EMWG, 2007). Fabrication in controlled factory environments: increases the quality of the components (e.g. reducing mistakes in construction and reworks); reduces construction schedules; reduces maintenance cost because of a reduction of the probability of failure of components; and supports safer construction processes (Boldon et al., 2014; Carelli and Ingersoll, 2014; Maronati et al., 2017). Furthermore, factory fabrication could determine a cost-saving in labour and construction. By contrast, the supply chain start-up cost is expected to be high (UxC Consulting, 2013). The expected higher cost of transportation activities is a further disadvantage of modularisation (Carelli and Ingersoll, 2014; Mignacca et al., 2019; UxC Consulting, 2013). (Mignacca et al., 2018) review the cost reduction (an average of 15%) and schedule saving (an average of 37.7%) resulting from the transition from stick-built construction to modularisation in infrastructure projects. Therefore, by implication, modular MSRs might have a lower cost and a shorter schedule than stick-built MSRs. However, challenges and costs typically associated with modularisation such as setting up a supply chain and module transportation, need to be carefully considered.

3. Methodology

This paper provides an SLR combining the methodologies presented by (Di Maddaloni and Davis, 2017; Mignacca and Locatelli, 2020; Sainati et al., 2017). Starting from the research objective “to critically summarise the state-of-the-art about MSR economics and finance and the most relevant gaps in knowledge”, the selection process of the documents includes two sections. Section A deals with academic documents extracted from the search engine Scopus, and Section B deals with the industrial literature (e.g. documents mostly provided from reactor vendors) and reports published by relevant organisations (e.g. International Atomic Energy Agency).

Section A has three main stages. The first stage is the identification of relevant keywords related to the research objective. Discussions with experts and several iterations led to the following list:

- MSR: “*Molten salt reactor*” and “*MSR*”;
- Economics: “*Economic*” and “*Cost*";
- Finance: “*Finance*” and “*Financing*”.

In the second stage, the following search string was developed with the Boolean operator *AND*/*OR* and introduced in Scopus to search the relevant literature:

- “*Molten Salt Reactor*” OR “*MSR*” AND “*Economic*” OR “*Cost*” OR “*Finance*” OR “*Financing*” (search date: 05/06/2020).

Scopus was chosen because of its international coverage from major scientific peer-reviewed journals, conference papers, and books. A timeframe was not selected a priori (therefore it is 1966–2020). The selection step retrieved 476 documents by using the aforementioned string (applied to title, abstract or keywords), excluding 52 non-English documents (not related to the research objective).

The third filtering stage is characterised by the following two steps:

1) Carefully reading the title and abstract of each document, screening out documents not related to the research objective or duplication. After the first step, 461 documents were screened out.
2) Carefully reading the introduction and conclusion of each document retrieved after the first step, screening out documents not related to the research objective. After the second step, 11 documents were screened out, leaving 4 documents to be analysed: (Moir, 2002), (Moir, 2008), (Samalova et al., 2017), and (Richards et al., 2017).

Fig. 1 summarises the selection process for Section A.

Furthermore, following discussions with experts, (MIT, 2018) which provides relevant information about MSR economics and finance was added.

In section B of the selection process, documents were firstly searched on reactor vendor websites with the aim to retrieve information about economics and finance of MSRs. Vendor websites often provide links to external sources. External sources reporting information about economics and finance of MSRs were therefore consulted. Secondly, documents were searched on the IAEA (International Atomic Energy Agency) and NEA (Nuclear Energy Agency) websites (section: publications). IAEA and NEA were selected because they are leading organisations in the nuclear field and publish high-quality reports. Two keywords related to MSRs were used to search documents on the IAEA and NEA websites: “Molten Salt Reactor” and “MSR” (search date: 05/06/2020). However, there are no publications focusing on economics and finance of MSRs. After discussions with experts, the Advanced Information Reactor System (ARIS) was consulted. ARIS is an IAEA reactor database reporting several MSR designs and related documents providing information about MSR economics and finance.

4. What we know about the economics and finance of MSRs

This section gives an account of the state of the literature about economics and finance of MSRs following two main streams: scientific and industrial literature. For the sake of transparency and reproducibility, quantitative data from the retrieved documents are reported in section 4.1 and 4.2 and scaled to 2020 prices ($) in section 4.3 (summary and comparison).

4.1. Scientific literature

The scientific literature about the economics of MSRs is very scarce and almost non-existent in terms of their financing. Four scientific papers were retrieved from the SLR [(Moir, 2002),[2] (Moir, 2008),[2] (Samalova et al., 2017), (Richards et al., 2017)], and (MIT, 2018) was added after discussions with experts.

(Moir, 2002) estimates the MSR LCOE and benchmarks this value with comparable PWR and coal plant estimates, based on the evaluations of the ORNL in 1978 (Engel et al., 1980, 1978). According to (Moir, 2002), a cost breakdown and description of a 1000 MWe MSR, an equal size PWR and coal plant were presented in the ORNL report; all of them NOAK plants. Starting from this report and other sources (Moir, 2002), reaches the following two main results:

- LCOE of a 1000 MWe MSR (20% enriched): $36.5/MWh;
- LCOE of a 1000 MWe MSR is 7% lower than an equal size PWR and 9% lower than an equal size coal plant.

[2] (Moir, 2008, 2002) seem to calculate the LCOE in a simplified manner without considering time-dependent aspects such as cash flow discounting.

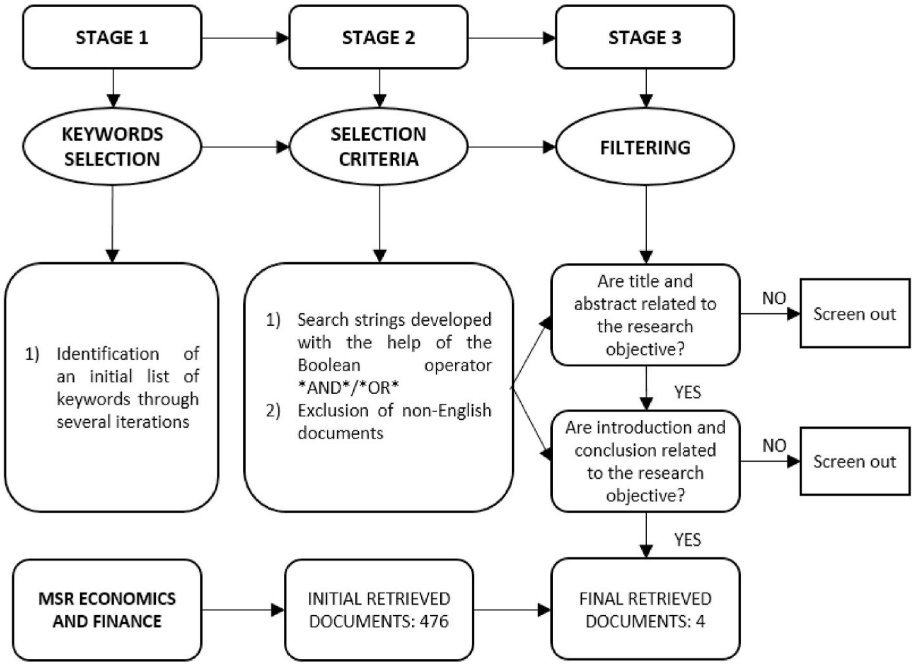

Fig. 1. Section A of the selection process – Layout adapted from (Di Maddaloni and Davis, 2017).

However, the analysis does not consider the impact on the cost of several items such as safety, licensing, and environmental standard.

(Moir, 2008) also compares the LCOE of a 1000 MWe MSR (20% enriched), a 1000 MWe MSR (100% enriched), a 1000 MWe PWR and a 1000 MWe coal plant. Table 1 summarises the comparison; it is worthy of highlight that the enrichment has to be lower than the non-weapon grade for industrial and commercial plants (<20% ^{235}U or <12% ^{233}U) (Moir, 2008; Siemer, 2019). The difference between the LCOE of the two analyses [(Moir, 2002) and (Moir, 2008)] is due to a different capacity factor (95% vs 90%).

(Samalova et al., 2017) compare cost estimations of three different Integral Molten Salt Reactors (IMSRs) (IMSR600, IMSR300, and IMSR80) and an Advanced Passive PWR (AP1000), using the methodology developed by the GIF Economic Modelling Working Group (GIF/EMWG, 2007). (Samalova et al., 2017) follows a top-down approach, because of the lack of data precluding a bottom-up approach.

Table 2 shows the calculated total Overnight Cost (OC) [M$] and the OC [$/kWe] for the AP1000 and three different IMSRs.

Table 2 highlights how the IMSR's total OC is about one-quarter of AP1000's total OC. However, considering that the IMSR's power output is one-third of AP1000's one, the OC per kWe is comparable. The IMSR80 is characterised by a significantly higher OC per kWe, but also by a significantly lower total OC. (Samalova et al., 2017) also calculate and compare the AP1000's LCOE and IMSRs' LCOE (Table 3) and the relative share of LCOE components for AP1000, IMSR600, IMSR300 and IMSR80 (Fig. 2).

(Samalova et al., 2017) highlight that the AP1000 presents a capital cost share slightly higher than the IMSR600. Considering that the AP1000 has about three times higher power output, it is expected that the IMSR600 capital cost share would be lower if IMSR600 and AP1000 are compared with the same power output (Samalova et al., 2017). Furthermore, (Samalova et al., 2017) carry out an LCOE sensitivity analysis to the discount rate (3% low scenario, 5% base scenario, 10% high scenario). Fig. 3 summarises the results. In another study, (Richards et al., 2017) calculate the MSR's LCOE under different OCs ranging from $2000/kWe to $7000/kWe ($2000/kWe is the lower manufacturers estimation, $7000/kWe is a reasonable high end). Fig. 4 summarises the results.

(Richards et al., 2017) compares the cost of various electric grid scenarios introducing MSRs, considering the following costs of nuclear power:

- MSR OC: $3000/kWe;
- Light water SMR OC: $5028.58/kWe;
- Large scale LWR OC: $5451.86/kWe;
- Variable MSR O&M costs assumed the same as large scale LWRs;
- Fixed MSR O&M costs assumed to be similar to light water SMRs.

Table 1
LCOE [$/MWh] MSR - PWR – coal. Adapted from (Moir, 2008).

Components	MSR (20% enriched)	MSR (100% enriched)	PWR	Coal
Capital	20.1	20.1	20.7	15.8
O&M	5.8	5.8	11.3	8.0
Fuel	11.1	4.0	7.4	17.2
Waste disposal	1.0	1.0	1.0	0.9
Decomposition	0.4	0.4	0.7	–
Total	38.4	31.3	41.1	41.9

Table 2
AP1000 and IMSRs total overnight cost - Adapted from (Samalova et al., 2017).

Case	MWe	Total Overnight Cost [M$]	Overnight Cost [$/kWe]
AP1000	1000	3249.105	2972.57
IMSR600	291	829.456	2850.37
IMSR300	141	524.450	3719.51
IMSR80	32.5	297.840	9164.31

Table 3
AP1000 and IMSRs LCOE (Discount rate: 5%) - Adapted from (Samalova et al., 2017).

Components [$/MWh]	AP1000	IMRS600	IMSR300	IMSR80
Capital cost	20.79	21.92	28.60	70.48
Operational cost	9.23	13.85	17.15	44.73
Fuel cycle – Front End	7.95	7.01	7.44	9.25
Fuel cycle – Back End	1.24	1.20	1.21	1.24
D&D Sinking Fund	0.16	0.15	0.17	0.35
Total [$/MWh]	**39.38**	**44.13**	**54.58**	**126.05**

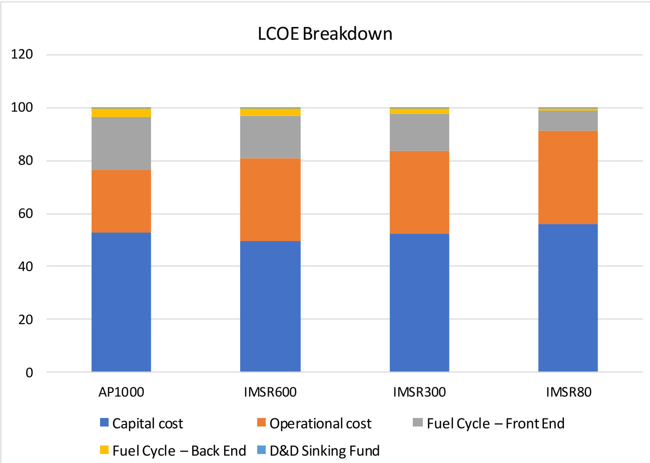

Fig. 2. LCOE breakdown [%] for AP1000, IMSR600, IMSR300, IMSR80 - Data from (Samalova et al., 2017).

In order to compare several scenarios, the authors start from the following base case using the US electricity generation mix: coal (33%), natural gas - combined cycle (32%), LWR (20%), hydropower (6%), wind (4.7%), natural gas – combustion turbine (1.7%), biopower (1.6%), solar - photovoltaic (0.6%), and geothermal (0.4%). (Richards et al., 2017) analyse several scenarios, but those focusing on MSRs are:

- Replacing coal with light water SMRs and MSRs (16.5% each); this replacement determines an overall cost reduction of 8.3%;
- Replacing LWRs with MSRs; this replacement determines an overall cost reduction of 10% (mostly due to the lower OC).

In another study, (MIT, 2018) provides a detailed capital cost estimation of the ORNL 1000 MWe MSR scaled to 2014, as summarised in Table 4. Furthermore, (MIT, 2018) provides a capital cost comparison between several NOAK advanced reactors: High-Temperature Gas-cooled Reactor (HTGR), SFR, Fluoride salt-cooled High-temperature Reactor (FHR) (Large), FHR (Small), and MSR (summary in Fig. 5).

(MIT, 2018) cost estimation is based on stick-built construction in the US for a NOAK plant. NOAK plant is considered identical to the FOAK, except for some site-specific characteristics. MSR direct costs have been calculated from an early-1980s pre-conceptual design escalating them to 2014$. Indirect costs have been considered as a percentage of the direct costs because of the lack of information. Furthermore, a contingency based on the design maturity, related technology development and supply chain considerations has been considered (20% for HTGR and SFR, and 30% for FHR and MSR). The key hypotheses are a construction time of 60 months and an interest rate of 8% (50% debt and 50% equity financing, 30 years as the economic life of the plant). Furthermore, (MIT, 2018) reports an LCOE estimation of the ORNL 1000 MWe scaled to 2014 of $119.25/MWh.

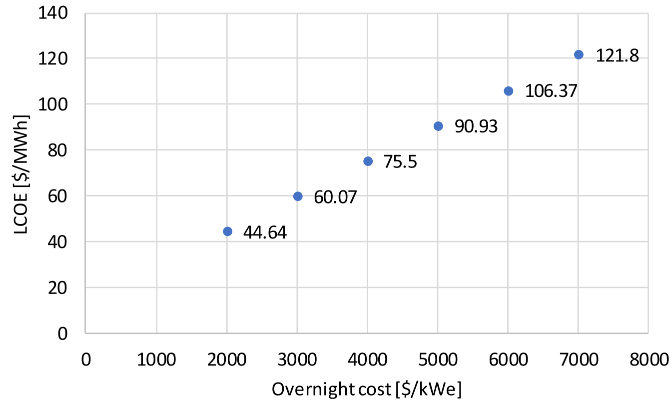

Fig. 4. MSR overnight cost sensitivity analysis - Data from (Richards et al., 2017).

4.2. Industrial literature

This section summarises the information retrieved from Section B of the SLR. Some MSR designs have not been included in this section because, at the time of writing, there is no public information about their economics and finance. For each design, firstly economic information from vendor websites are briefly presented (where available). Secondly, economic information from external industrial documents/websites are summarised (where available). Lastly, financial information from both vendor websites and external sources are summarised (where publicly available).

4.2.1. Terrestrial Energy's integral Molten Salt Reactor

Terrestrial Energy's 195 MWe IMSR uses graphite as moderator and molten salts as coolant (Terrestrial Energy, 2017a). Terrestrial Energy's

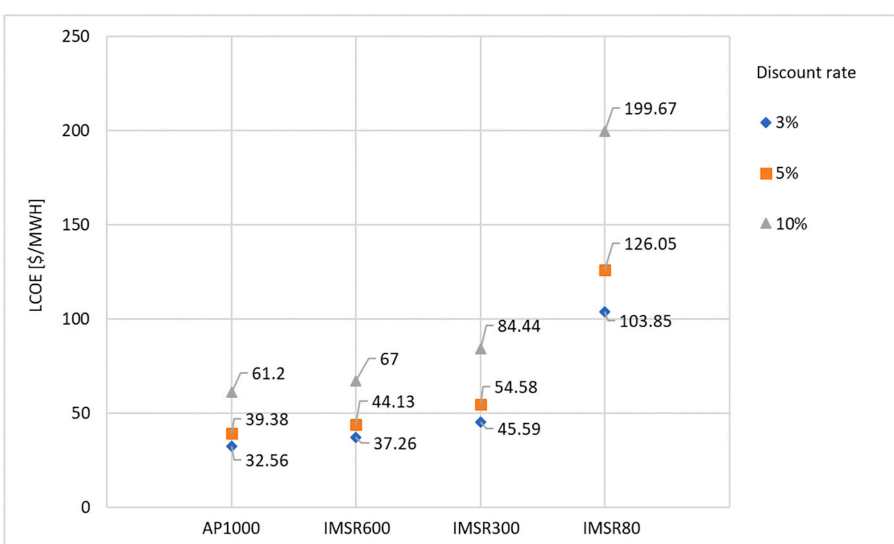

Fig. 3. LCOE sensitivity analysis to the discount rate – Data from (Samalova et al., 2017).

Table 4
ORNL 1000 MWe MSR - MIT Cost estimation Adapted from (MIT, 2018).

Cost items	[$/kWe]	Total [$/kWe]
Direct costs		
Structures and improvements	659	
Reactor plant equipment	870	
Turbine plant equipment	440	
Electrical plant equipment	266	
Miscellaneous plant equipment	159	
Main Cond heat reject system	61	**2455**
Indirect Costs		
Owner's costs	% Direct	
Construction services	% Direct	
Home Office Engine & Service	% Direct	
Field Office Engine & Service	% Direct	**1669 (68%)**
Base cost		**4125**
Contingency		**1237 (30%)**
Total overnight cost		**5362**
Interest during construction		**751 (20%)**
Total [$/kWe]		**6113**

IMSR is envisaged to adopt modularisation as a construction strategy. The modular approach would allow the 195 MWe IMSR power plant to be built in 4 years, requiring an upfront investment of less than 1 B$ (Terrestrial Energy, 2017b). According to (Terrestrial Energy, 2017b), IMSRs can dispatch power at under $50/MWh.

ARIS reports the IMSR-400, characterised by an electrical capacity of 194 MWe per module (IAEA, 2016a). However, according to (WNA, 2018), there are three proposed sizes of the Terrestrial Energy's IMSRs: 80 MWt (32.5 MWe), 300 MWt (141 MWe), and 600 MWt (291 MWe). These three sizes are equivalent to those presented in the scientific literature on IMSRs (i.e. (Samalova et al., 2017)). (Terrestrial Energy, 2015) states that IMSR600 and IMSR300 levelised cost is estimated respectively $43 and $59 per MWh. Furthermore, (NEI, 2016a) reports an interview with the Terrestrial Energy CEO, stating that the levelised cost of the plant for a 300 MWe IMSR is projected at $40-$50/MWh.

Regarding IMSR financing, Terrestrial Energy website reports several links to external sources. The retrieved information are categorised by year and presented in chronological order.

In 2016, Terrestrial Energy raised:

- 7.1 M$ in venture capital for IMSR technology development (NEI, 2016b);
- 4.4 M$ from Sustainable Development Technology Canada for IMSR pre-commercial activities (Nuclear Street News, 2016);
- 4 M$ (unspecified how), leading to 17.2 M$ received from its inception (Cantech letter, 2016).

Furthermore, in 2016, the US Department of Energy (DOE) invited Terrestrial Energy to submit the second part of its application for a US federal loan guarantee. Terrestrial Energy applied for a loan guarantee of between 800 M$ and 1.2 B$ (World Nuclear News, 2016).

In 2018, Terrestrial Energy received a technology development voucher of 0.5 M$ from the US DOE (DOE, 2018).

4.2.2. MSR-FUJI

MSR-FUJI is a size-flexible (100 MWe–1000 MWe) MSR which uses graphite as moderator and fluoride salt as coolant. It has been developed since the 1980s by a Japanese group (now, International Thorium Molten-Salt Forum: Japanese, Russian and US consortium) based on the ORNL results (IAEA, 2016b; International Thorium Molten-Salt Forum, 2017; WNA, 2018). The developer's website (International Thorium Molten-Salt Forum, 2017) does not provide economic or financial information.

According to (IAEA, 2016b), the typical MSR-FUJI design is 200 MWe and can be considered an SMR (IAEA, 2016b). The estimated construction cost of the 1000 MWe MSR-FUJI is less than $2000/kWe

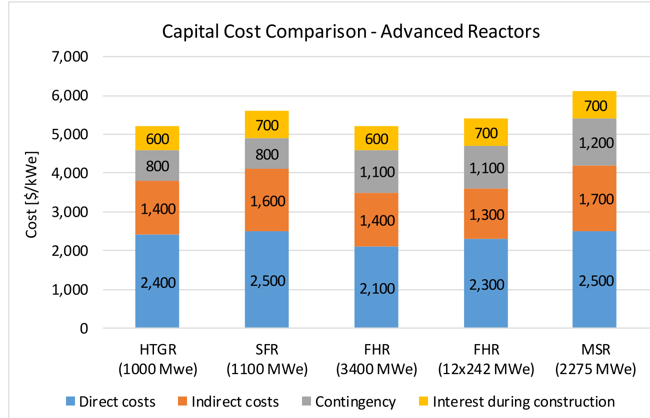

Fig. 5. Capital cost comparison - Advanced reactors - Adapted from (MIT, 2018).

and the total electricity generation cost is about $30/MWh (IAEA, 2016b).

4.2.3. ThorCon MSR

The ThorCon is a 250 MWe scaled-up Oak Ridge MSR Experiment, designed by Martingale in the US, which uses graphite as moderator and a mixture of sodium and beryllium fluoride salts as coolant. Thorcon NPP drawing presents two 250 MWe power modules (ThorCon, 2018). (ThorCon, 2019) reports a capital cost estimation of $800–1000/kWe and an electricity generation cost of $30/MWh for a 500 MWe ThorCon NPP.

ARIS reports the 250 MWe per module (IAEA, 2020b). According to (WNA, 2018), the company claims generation costs of $30–50/MWh (depending on scale).

4.2.4. Moltex Energy's stable salt reactor (SSR)

Moltex Energy's SSRs are modular with a size flexible from 150 MWe to 1200 MWe. Moltex Energy commissioned a cost estimation from Atkins Ltd (nuclear engineering company), which estimated a cost to build a NOAK 1 GWe SSR of $2083/kWe, putting the cost range at $1339-3703/kWe (Energy Economist, 2015). (NEI, 2016c) reports an interview with the Moltex' Energy Chief Operating Officer, stating that the capital cost of 1 GWe SRR is estimated at $1950/kWe and the LCOE at $44.64/MWh.

Regarding its financing, Moltex Energy website (www.moltexenergy.com) provides information about its financing in the period 2018–2020, also providing links to external sources.

Moltex Energy received in 2018:

- a £300k contract by the UK Government in order to develop a feasibility study for SSR deployment in the UK (Moltex Energy, 2018a); and
- 5 M$ of financial support from New Brunswick Energy Solutions Corporation and New Brunswick Power to continue the development of the SSR-Wasteburner technology in New Brunswick (Moltex Energy, 2018b).

In 2019:

- 2.5 M$ from IDOM Consulting, Engineering, Architecture SAU in order to accelerate the SSR pre-licensing progress through Vendor Design Review and expand New Brunswick office (Moltex Energy, 2019a, 2019b);
- around 7.5 M$ through crowdfunding to support the company through the pre-licensing process in Canada and business

development in the UK (around 170 investors contributed nearly half of the amount) (Moltex Energy, 2019c, 2019b; WNN, 2019); and
- 2.55 M$ from the US DOE to develop Composite Structural Technologies for SSRs (Moltex Energy, 2019d).

In 2020:

- an unspecified amount from Canadian Nuclear Laboratories to progress fuel development (Moltex Energy, 2020); and
- 3.5 M$ from the Advanced Research Projects Agency-Energy (i.e. an agency within the US DOE) to advance SSR technology.

4.2.5. *The Elysium's molten chloride salt fast reactor (MCSFR)*

The Elysium's MCSFR is a size-flexible (50–1200 MWe) MSR which uses Chloride based Fuel Salt as coolant (Elysium Industries, 2017). However, ARIS does not report on this type of MSR (IAEA, 2020b). Regarding MCSFR economics, (Elysium Industries, 2017) provides only a series of characteristics leading to cost implications:

- Simplified engineering systems with a natural technique for passive operation and safety;
- Simplified reactor control system eliminating human operator actions;
- It operates at relatively low pressure determining the reduction of the size and cost of the reactor, vessel and containment buildings with respect to conventional PWR;
- Solid fuel fabrication and validation are eliminated;
- Passive safety system determines the reduction of the cost associated with the emergency coolant injection system;
- It can be fuelled with spent nuclear fuel, partially addressing waste disposal issues.

The reactor presents a higher burnup than thermal water reactors, and the fuel can be reused in the subsequent reactor. In 2018, Elysium Industries received 3.2 M$ from the US DOE to develop the computational fluid dynamics models to simulate and optimise the flows of chloride molten salt fuel in a reactor vessel and heat exchangers (Energy Central, 2018). Furthermore, in 2018, Elysium Industries received 0.5 M $ from the US DOE to foster technology development (Office of Nuclear Energy, 2018).

4.2.6. *Transatomic Power's MSR*

Transatomic Power (TAP) modified the design of the 1960s Oak Ridge MSR using a zirconium hydride moderator instead of graphite (TAP, 2017). TAP ceased operation in 2018. TAP website reports the main reason: "*we haven't been able to scale up the company rapidly enough to build our reactor in a reasonable timeframe*" (TAP, 2018). TAP intellectual property will be open source (TAP, 2018). The envisaged first commercial NPP was 520 MWe, characterised by an estimated overnight cost for the NOAK of $3846.15/kWe (TAP, 2017). ARIS does not report on the TAP MSR (IAEA, 2020b).

Regarding TAP financing, TPA received 2 B$ from FF Science, an investment vehicle of Founders Fund (i.e. a San Francisco-based venture capital firm) in 2014 (TAP, 2014). In 2015, TPA received 2.5 B$ from Acadia Woods Partners, Peter Thiel's Founders Fund, and Daniel Aegerter of Armada Investment AG (TAP, 2015).

4.3. *Overall summary and comparison*

Table 5 summarises and compares the main economic information retrieved from the scientific and industrial literature. Data are scaled to $2020 using the CPI (Consumer Price Index) calculator provided by the US Bureau of Labor Statistics (US Bureau of Labor Statistics, 2020). When the reference year was not provided in the retrieved literature, the publication date was used as the reference year. Fig. 6 provides a general summary of the quantitative economic information about MSR LCOE, OC and Capital cost.

Table 5
Comparison and adjustment for inflation ($2020).

MSR data	LCOE [$/MWh]	Overnight cost [$/kWe]	Capital cost [$/kWe]	Sources
1000 MWe 20% enriched capacity factor (CP) 95%	55.78			Moir (2002)
1000 MWe 20% enriched CP 90%	58.69			Moir (2008)
1000 MWe 100% enriched, CP 90%	47.83			Moir (2008)
IMSR600 (291 MWe)	48.71	3146		Samalova et al. (2017)
IMSR300 (141 MWe)	60.25	4105		Samalova et al. (2017)
IMSR80 (32.5 MWe)	139.14	10,115		Samalova et al. (2017)
Size not specified (SNP)	49.23–134.33			Richards et al. (2017)
ORNL 1000 MWe	119.25	5913	6741	MIT (2018)
Terrestrial Energy (TE) IMSRs (SNP)	<53.12[a]			Terrestrial Energy (2017a)
TE IMSR 300 MWe	43.55[b]-54.44			NEI (2016a)
TE IMSR600 (291 MWe)	47.46[b]			Terrestrial Energy (2015)
TE IMSR300 (141 MWe)	65.13[b]			Terrestrial Energy (2015)
1000 MWe MSR-FUJI	32.67[c]	2,177[d]		IAEA (2016b)
ThorCon (500 MWe)	30.75[e]		819.89–1024	ThorCon (2019)
ThorCon-MSR (SNP)	31.22–52.04[f]			WNA (2018)
1 GWe Moltex Energy' SSR		2299		Energy Economist (2015)
1 GWe Moltex Energy' SSR			1478–4087	Energy Economist (2015)
1 GWe Moltex Energy' SSR	48.61		2123	NEI (2016c)
TAP 520 MWe		4085		TAP (2017)

[a] According to (Terrestrial Energy, 2017a), IMSRs can dispatch power under 53.12 $/MWh ($2020).
[b] These values are defined as "levelised cost" (NEI, 2016a; Terrestrial Energy, 2015).
[c] (IAEA, 2016b) defines it "total electricity generation cost".
[d] (IAEA, 2016b) defines it as "construction cost".
[e] (ThorCon, 2019) defines it as "electricity generation cost".
[f] (WNA, 2018) defines the range as "generation cost".

5. What we should know: a research agenda

In this section, the authors present the key areas that need further investigation, suggesting a research agenda.

5.1. *Economics*

Licensing cost and time. The process of licensing a nuclear design

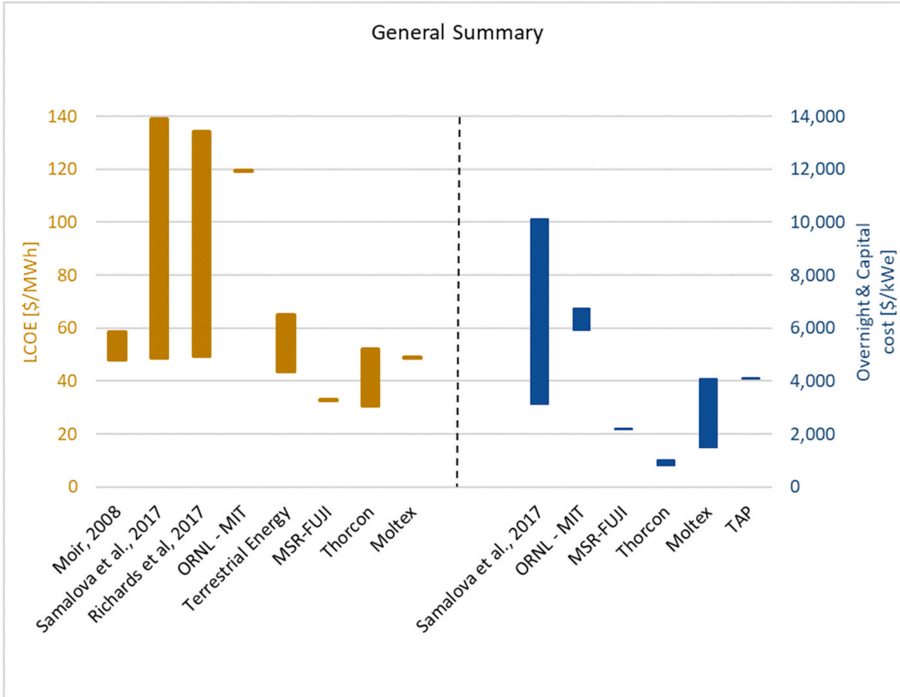

Fig. 6. General summary LCOE, Overnight and Capital cost ($2020).

is, particularly in the US and Europe, a lengthy and expensive process. Even for "classical PWR" the duration and cost are extremely relevant [e.g. 10 years for the AP1000 design to complete the UK regulatory assessment (Office for Nuclear Regulation, 2017a, 2017b)]. The more the NPP deviates from the "classical PWR" design, the longer and more expensive the licensing process is expected to be. For instance, the NuScale SMR design started the US NRC (Nuclear Regulatory Commission) pre-application process in 2008 (NuScale, 2020) and, at the time of writing, it has completed Phase 4 out of the 6 phases of the NRC's design review certification (World Nuclear News, 2019). In Canada, relatively few MSRs are completing pre-licensing vendor design reviews (Canadian Nuclear Safety Commission, 2020). Consequently, particularly for GEN IV reactors, there are a number of challenges across the licensing journey (Sainati et al., 2015). Therefore, more information about the process, cost, financing, time and risk involved in the licensing process would be useful.

Construction and operations – Reference plant. MSR proposed outlet temperatures are in the range of 700 °C – 850 °C. Long-term operation above 650 °C determines material challenges related, for instance, to the corrosiveness of fuel salt (MIT, 2018), which could determine the need for unproven and potentially expensive materials increasing the cost of the main components. Furthermore, the peculiar characteristics of MSRs can impact on O&M costs. For instance, in the case of MSRs using fluoride salt as coolant, lithium in the salt produces tritium which will permeate through hot structures requiring workers to use respirators to perform O&M (MIT, 2018). It is often unclear if these and other aspects (e.g. O&M activities during the circulation of dissolved fuel or long-term corrosion increasing the frequency of replacement components) are considered in the economic analysis. Furthermore, most of the analyses refer to very old documents (e.g. (Engel et al., 1980, 1978)) with limited information and potentially controversial assumptions. However, the lack of data determines the need for controversial assumptions in economic analyses. Building a prototype (even of few megawatts) could lead to additional insights, generating new data and thereby creating opportunities to carry out more reliable economic analyses and foster MSR commercial operation.

Fuel - Waste management and decommissioning cost. This is a relevant point since MSRs could help to deal with the waste from traditional LWRs (considering that MSRs can be designed as nuclear waste burners or breeders), but at the same time, even these reactors produce waste (although less high-level waste) (IAEA, 2020a). Moreover, unlike LWRs, the fuel used by MSRs is not a standard "industrial product" with several suppliers. Research is needed across the entire fuel cycle. This implies that the economics of the fuel cycle needs to be investigated considering both costs and, eventually, revenues. Similarly, the economics of decommissioning, already uncertain for LWRs (Invernizzi et al., 2017, 2019b; 2019a, 2020a), need substantial research for MSRs. (Mignacca et al., 2020b) introduce the Modular Circular Economy strategy to improve decommissioning in the general case of energy infrastructure, and (Mignacca et al., 2020a) discusses this strategy in the specific case of SMRs. According to (Mignacca et al., 2020a), SMR modules could be designed in a way that when the SMR plant reaches the end of life modules having still useful life can be reused in other plants. The implementation of this strategy has an impact on economics and finance, and it should be considered in future MSR SMR cost estimations and financial analyses.

5.2. Financing

Basis for estimate/third party assessment. As aforementioned, in several references (particularly industrial), the basis for the estimate are unclear. It is often unclear how the costs have been calculated (e.g. how the cost of the turbine has been established) and what has been included/excluded (e.g. owner costs, detailed design). A further research area would therefore be to develop a third-party assessment and standardisation of the cost estimation methods, thereby adding transparency and credibility to the estimates. Adding transparency and credibility to the estimates of both costs and revenues could attract investors. Similarly, a risk analysis is necessary to identify the key cost drivers, their magnitude and uncertainty.

Financing. Financing deals with questions such as "who is providing the money to build the reactor?", "Who is accepting the risk of cost escalation and will provide the money to cover extra-cost?". Most of the retrieved documents focus on MSR economics. The scientific literature neglects MSR financing, and information in the industrial literature is far from comprehensive about who is financing MSR technology development, i.e. mostly governments (e.g. US DOE) and private investors (e.g. Moltex crowdfunding). The financing of the next MSR development stages (e.g. financing NOAK MSRs) is not receiving the necessary attention. This is a common issue for the new advanced nuclear reactors where, in general, publications are scant (Boarin et al., 2012; EFWG, 2018; Mignacca and Locatelli, 2020; Sainati et al., 2020, 2019). Governments across the world are setting up task-forces to address these questions. The studies are often confidential with few exceptions, one being the work done in the UK (EFWG, 2018). Particularly relevant will be distinguishing the financing of the FOAK unit (a very high-risk investment) from the financing of the NOAK unit (where the risk has been reduced by the experience) (Locatelli and Mancini, 2012b).

Furthermore, the retrieved academic and industrial documents point out how the current literature focuses on LCOE (indicator relevant mostly for policy-makers), neglecting indicators of financial performance such NPV and IRR, which are relevant for utility companies (and investors in general) to measure the profitability and risk of the MSR investment. Further studies focusing on other indicators of economic and financial performance are needed.

Revenues. (MIT, 2018) point outs several other potential applications other than electricity production for MSRs, i.e. process heat for producing hydrogen, synfuels and other chemicals, and actinide transmutation for fast MSRs. These applications might ideally be combined with load-following (Locatelli et al., 2018, 2017), enabling potential revenues, which need to be carefully estimated in future economic and financial analyses.

6. Conclusions

MSRs are one of the six GEN IV technologies presented in (GIF, 2014, 2002), and as such share the economic goal of having *"a life cycle cost advantage over other energy sources"* (GIF/EMWG, 2007) (Page 9). If MSRs are potentially a relevant technology for the middle/long term, then the available knowledge about economics and finance of MSRs is very limited, fragmented and in need of further investigation. This paper provides a structured summary of the knowledge about "economics and finance" of MSRs, following two main streams: scientific and industrial literature.

Regarding the scientific literature, only four papers are strictly related to the research objective, focusing on MSR economics whilst neglecting their financing. (Moir, 2008, 2002) point out that a 1000 MWe MSR is characterised by an expected LCOE lower than an equal size PWR and an equal size coal plant. The analysis carried out by (Samalova et al., 2017) points out how the IMSR cost structure is expected to be similar to the PWR one. Generally, MSRs might not need a thick containment unit like LWRs and are characterised by higher temperature determining an increased thermal efficiency. These two characteristics are the main factors determining an expected lower capital cost than LWRs (Moir, 2008; Richards et al., 2017). Manufacturers estimate an overnight cost between $2000/kWe and $4000/kWe for a NOAK MSR (Richards et al., 2017).

Regarding the industrial literature, this paper provides a brief introduction to several MSR designs, followed by economic and financial information. MSR designs have been selected according to the availability of economic and financial information. The results of the industrial literature review analysis show that there are very few economic and financial studies about MSRs, and in most cases, they are provided by reactor vendors with evident conflict of interest. The financing of MSR technology development is met by governments (e.g. US DOE) and private investors (e.g. Moltex crowdfunding). However, the financing of the next stages (e.g. financing NOAK MSR) is not receiving enough attention yet.

In summary, the key takeaways from this paper about the economics and finance of MSRs are:

- There is very limited information on economics and finance. Particularly in the scientific literature where information is very scarce and focuses on MSR economics. The information about MSR economics and finance provided by vendor websites and other external sources (i.e. IAEA) is also fragmented. In general, indicators of financial performance (e.g. NPV, IRR, and LACE) are neglected from both scientific and industrial literature.
- The low quality of the information. The literature does not use a standard method to assess economics and finance, limiting the reliability of the comparison and hindering a critical and in-depth analysis of the data.
- MSRs have a cost breakdown structure similar to LWRs. As shown in Fig. 2, MSRs will be capital intensive.
- There are several gaps in knowledge, as highlighted in Section 5. MSR decommissioning cost and MSR financing represent huge gaps in the literature.
- MSR competitiveness. Based on the literature, MSRs are expected to be cost-competitive with other energy sources. However, further studies are needed.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the UK Engineering and Physical Sciences Research Council (EPSRC) grant EP/N509681/1. Furthermore, this work was partially supported by the Major Project Association (MPA). The authors are very grateful to the ESPRC and MPA. The authors also wish to thank Mr Ata Babaei, Dr Marco Colombo and Dr Kate Lawrence, who provided substantial feedback. The authors also acknowledge the substantial contribution of the reviewers. The opinions in this paper represent only the point of view of the authors, and only the authors are responsible for any omission or mistake. This paper should not be taken to represent in any way the point of view of MPA or EPSRC or any other organisation involved.

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