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Economics and finance of lead fast reactors: A systematic literature review

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ABSTRACT

Generation IV (Gen-IV) nuclear reactor designs are receiving increasing attention because of their potential to achieve key goals in terms of sustainability, safety, reliability, and economics. One of the six technologies selected in the Gen-IV program is the lead-cooled fast reactor (LFR). This work focuses on LFRs, examining both pure lead and lead-bismuth eutectic designs. Through two systematic literature reviews, we consolidate the state-of-the-art in economics and finance for LFRs. The first review considers scientific literature and retrieves 12 articles. The second focuses instead on industrial literature, resulting in 12 additional documents. Economics literature is very scarce and sometimes of low quality. Economic estimations for the specific capital cost [$/kWe] and the cost of electricity [$/MWh] can vary by an order of magnitude (1500–25000 $/kWe and 30–350 $/MWh, respectively), while design organizations typically do not publicly share financial details. Finance literature is almost nonexistent. We report, in the final part of the work, notable knowledge gaps and further possible research areas.

1. Introduction

Gen-IV nuclear energy systems are defined as "revolutionary" due to their discontinuity with the Gen-III/III+ systems, predominantly based on light water designs (LWR) (GIF, 2014). The Gen-IV International Forum (GIF) identifies six technologies as part of the Gen-IV designs (GIF, 2014):

- *GFR (Gas Cooled Fast Reactor)*, helium-cooled, aims to combine a fast spectrum core with a high-temperature reactor.
- *LFR (Lead Cooled Fast Reactor)*, fast spectrum liquid metal reactor cooled by lead (Pb) or lead-bismuth eutectic (LBE), designed for electricity production and management of actinides.
- *MSR (Molten Salt Reactor)*, a fast or thermal reactor cooled by liquid molten salts and usually moderated by graphite, fuel can either be solid or liquid.
- *SCWR (SuperCritical Water Reactor)*, fast or thermal reactor cooled by supercritical water.
- *SFR (Sodium Cooled Fast Reactor)*, a fast spectrum liquid metal reactor cooled by sodium.
- *VHTR (Very High-Temperature Reactor)*, thermal reactor cooled by helium and moderated by graphite.

For this study, we chose to focus on the LFR technology due to its growing significance and attention both in Europe and globally. Numerous LFR designs are in various stages of development. Some interesting projects are listed in Table 1.

The LFR technology has a series of positive characteristics, leading to a simple, cost-effective, and inherently safe design:

- Both Pb and LBE have very high boiling points. This allows the reactors to operate at atmospheric pressure and higher temperatures than typical GEN-III/III+ NPPs. This mitigates the risk of coolant boiling and core voiding, reducing safety challenges, and enabling simplification of design, safety demonstration, and high power conversion efficiency even above 42% (GIF, 2014).
- Pb and LBE coolants exhibit minimal interactions with water or air. This simplifies the design and reduces costs by removing the need for a complex and expensive intermediate circuit to isolate the primary coolant (Alemberti, 2021).
- Heavy metal coolants offer high thermal capacity, providing significant thermal inertia in case of an accident. Their high density minimizes the risk of re-criticality in the event of core melting because it would float on top of the coolant (Grasso et al., 2010).

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- Pb and LBE have very good retaining properties up to 600 °C, potentially enabling a reduction of the emergency planning zone (Grasso et al., 2010). Their low moderation capabilities allow greater spacing between fuel pins, reducing pressure drops and the risk of flow blockage while maintaining the possibility of natural convection (GIF, 2014).
- Due to the scattering properties of heavy metals, LFRs operate with a fast neutron spectrum. This enables the association of a closed fuel cycle with the reactor system to recover the uranium and transuranic elements back to the core. Waste production is primarily from fission products and losses from reprocessing and fabrication. The fuel cycle cost can be reduced by achieving high burnup, particularly from oxide and nitride fuels compatible with LFRs (Grasso et al., 2010).
- Lastly, LFRs facilitate load following operation due to the small difference between the "cold state" temperature and the operational one. The system may be coupled with auxiliary plants for cogeneration or for additional energy storage (Alemberti, 2021).

However, before commercial operations, several challenges must be addressed and require further research and development (R&D):

- A closed fuel cycle is technically complex. It involves the chemical reprocessing of spent fuel, requiring specialized expertise and strict regulatory compliance. Proliferation concerns may arise because safe treatment and management of radioactive materials are essential to prevent misuse and accidents (Grasso et al., 2010).
- At high temperatures and high flow, Pb and LBE become highly corrosive. The LFR requires coolant chemical control, especially for oxygen, for the prevention of erosion and corrosion on structural steels. This demands careful material selection, and components and systems monitoring during operation. Coolant purification is needed and must be carefully controlled to minimize the chances of deposits and blockages (Alemberti, 2021).
- Pb and LBE are opaque and heavy, creating challenges regarding the inspection and monitoring of in-core components, fuel handling, and earthquake hazards given the increased density of the coolant.
- Pb must be maintained at a sufficiently high temperature to avoid freezing (melting temperature of 327 °C). This requirement is less stringent for LBE (melting temperature of 123 °C).
- Accumulation, trapping, and removal of volatile ^{210}Po (strong α-emitter, half-life of 138 days, its production is 100 times stronger for LBE than pure Pb) is also required (Alemberti, 2021).
- The cost and world availability of bismuth pose concerns because reserves are not well known (USGS, 2023), their last estimation of 370000 tons is from 2017 (USGS, 2017). The MYRRHA reactor, 100 MWt, needs 7800 tons of LBE coolant (SCK-CEN, 2018) corresponding to around 4000 tons of bismuth.

Given such a promising but challenging technology, a lot of research and development has to be expected. Deployment could be possible soon, especially for demonstrator reactors. Therefore, an analysis of the economics and finance of LFR is important to understand its attractiveness in the market. However, LFR literature predominantly focuses on technical aspects while mentioning only qualitatively the economic and financial aspects. This paper aims to critically summarize the state-of-the-art in economics and finance for such technology. This is performed via systematic literature reviews (SLR). The article is structured as follows: Section 2 introduces key economic and financial concepts which will be used in this work and by the documents considered, Section 3 describes in detail the methodology used to perform the SLRs. Section 4 presents all the considered documents, and Sections 5 and 6 respectively describe the most relevant knowledge gaps and conclude this work.

2. Economic and financial concepts

This paper deals with the economics and finance of LFRs, and therefore, it is important to clarify the difference between these two concepts. Economics studies the management of goods and services and what affects them. It deals with cost estimations and identification of cost drivers (e.g., construction costs and construction techniques). Economic analysis usually excludes the payments of taxes, remuneration, and debt amortization. It may include and quantify externalities, positive or negative, e.g., the reduction of greenhouse gas emissions (Brigham and Ehrhardt, 2008). Finance focuses on cash flows or equivalent means. It involves the study of credit and debt, securities, and investments for current projects using future income flows. It is used to document the expected return on investment for investors. It includes taxes, remuneration, amortization, etc., without including externalities (Brigham and Ehrhardt, 2008). Because of this temporal aspect, finance

Table 1
Extract of some commercially oriented and interesting LFR concepts.

Design name	Coolant	Thermal power [MWt]	Electrical power [MWe]	Status	Country of siting/ development	Reference
ALFRED	Pb	300	120	Development of detailed design	Romania	Alemberti et al. (2020)
BLESS	LBE	300	100	Conceptual design	China	Wang et al. (2017)
BREST-OD-300	Pb	700	300	Under construction	Russian Federation	WNA (2021)
CLEAR-I	LBE	10	–	Conceptual design	China	Wu et al. (2016)
CLFR	Pb	740	300	Conceptual design	China	Lin et al. (2019)
DFR	Molten salt + Pb	Expected 3000	–	Conceptual design	Germany	Wang et al. (2015)
ELFR	Pb	1500	600	Conceptual design	EU	Alemberti (2012)
LFR-AS-200	Pb	480	200	Development of detailed design	Italy, France, UK	Cinotti et al. (2018)
MYRRHA	LBE	100	–	Development of detailed design	Belgium	SCK-CEN (2018)
RBEC-M	LBE	900	340	Conceptual design	Russian Federation	Mikityuk et al. (2002)
SEALER	Pb	140	55	Conceptual design	Sweden	IAEA (2021)
SSTAR	Pb	45	20	Conceptual design	USA	Smith et al. (2008)
SVBR-100	LBE	280	100	Development of detailed design	Russian Federation	WNA (2021)
TORIA	LBE	30	–	Conceptual design	South Korea	Lee and Shim (2019)
URANUS	LBE	100	40	Conceptual design	South Korea	Choi et al. (2012)
W-LFR	Pb	950	460	Development of detailed design	USA	Ferroni et al. (2019)

is linked to the time value of money, interest rates, and other related topics (Investopedia, 2022). Therefore, calculating the construction cost of a nuclear power plant (NPP) is part of the economic study, but determining who will pay for it, and how, is part of the financial one. The next paragraphs offer an overview of the main economic and financial concepts used in the rest of the paper.

Cost and Price. In this work, we will often use the term "cost". The cost of a product or service is the sum of all the expenses required to manufacture or provide it. The price for the same product or service is the amount the customer pays for it, and it is usually market-driven or determined by policy decisions.

Top-down vs. Bottom-up approach. Quite common cost estimation approaches. In the top-down one, a proposed new project is compared to an already existing and hopefully similar one. Its cost is estimated by adjusting cost items such as materials, equipment, and technology. This is common and preferred when not much information regarding the project is available. In the bottom-up approach, the estimation of the total cost is the sum of the costs of each element (i.e., equipment, materials, labor, other services, etc.). This is performed if sufficient information is available because it requires detailed data about the project.

Direct & Indirect Costs, Contingency. Direct costs are those closely related to the construction of the NPP, including preparation of the site, labor costs, and reactor and turbine plant equipment. They typically exclude, e.g., support services. Indirect costs comprise all the support services (e.g., construction supervision) and all the ones not directly related to the construction of the plant (i.e., design services, procurement, quality inspections, fees, taxes, etc.). Contingency is an addition that provides an allowance for NPP cost uncertainties. It does not include external factors such as political decisions, labor strikes, extreme weather, etc. (Delene and Hudson, 1993).

Costs of an NPP. In principle, different economic performance indicators could be used for an NPP (IAEA, 2007). For this work, and most of the documents retrieved for the SLRs, the costs during the life cycle are divided into the following four parts:

- *Capital cost.* The sum of two components: the "overnight" capital cost and the interest during construction. In Delene and Hudson (1993) the "overnight" capital cost is defined as the initial estimation of the construction cost before any adjustments plus the owner's cost (e.g., site, project management), contingency, and first core cost (i.e., as built overnight).
- *O&M costs.* Operation and maintenance. Every cost that is needed to maintain and operate the NPP, except fuel costs (Delene and Hudson, 1993). Usually divided into fixed (e.g., plant staffing, security; they represent the biggest fraction of O&M costs) and variable ones (e.g., all consumables, replacement of worn parts; they are all the costs dependent on the electricity production).
- *Fuel costs.* They represent every activity of the fuel cycle, from the mining of the ore to the final radioactive waste disposal. They comprehend enrichment, reprocessing, and research activities related to the fuel cycle (IAEA, 2006).
- *Decommissioning costs.* They include all the costs from the planning of decommissioning until the final remediation of the site, including decontamination, dismantling, and waste management (IAEA, 2006). Sometimes called decommissioning and decontamination (D&D) costs.

Economic indicators. The documents we examined provide quantitative evaluations of the total plant cost and/or the electricity price. To standardize these evaluations, we chose two different economic indicators:

- the specific cost of the plant, often measured in [$/kWe], facilitates the comparison across different NPP sizes;
- the electricity cost (also called Levelised Cost of Electricity, LCOE, or Levelised Unit Electricity Cost, LUEC), measured in [$/kWh], to assess the economic competitiveness of the considered LFR. The LCOE is usually computed considering all the life-cycle costs of the NPP.

All the documents discussed in the paper will be presented using the value originally reported, i.e., are not escalated to consider time. However, to confront references written in different years, we corrected the values to consider time, reporting the results in Section 4.3.

Approaches for cost reduction. In the nuclear sector, different approaches to reduce NPP costs are often considered, the most common being:

- *Economy-of-scale.* According to this principle, the total cost of a plant increases with its size. However, its specific cost and the electricity one typically decrease. The reasons are both geometrical and economical (Locatelli et al., 2014): volumes and produced electricity increase to the power of 3, while areas and materials to the power of 2. Additionally, the licensing process is performed on a larger electrical power output, and fixed or semi-fixed costs may be shared. A few drawbacks of the economy-of-scale are driving attention to small modular reactors (SMRs), as presented by Mignacca and Locatelli (2020b). These include the larger capital investment and the complexity of GW-scale NPPs.
- *Economy of multiples.* The cost of an NPP also depends on the number of similar or identical units built on the same site, country, or worldwide. Two important factors come into play (Locatelli, 2018). The first is the learning process. Learning to build NPPs reduces the cost of equipment, materials, work, and the construction schedule. Indeed, each construction day adds fixed costs (i.e., working staff, equipment use, etc.) and postpones the production and sale of electricity. This increases the interest to be paid and reduces the present value of future cash flow. It is expected that the unit cost of a First-of-a-Kind (FOAK) would be higher than the Nth-of-a-Kind (NOAK) one. The learning process may be considered on a world level or a country level with the latter being stronger because regulatory frameworks may vary significantly among different countries (Locatelli, 2018). The second factor is the co-siting of units. Some fixed costs are saved when installing a second or subsequent unit on the same site, lowering the total investment of the co-sited units (i.e., acquisition of land rights, connection to the transmission network, cost of upgrades that can be shared, etc.) (Locatelli, 2018).
- *Modularization.* This construction strategy is not new and has important benefits if correctly applied for the construction of NPPs (Lloyd et al., 2021). The primary objective is to maximize the use of factory-based processes. Factories provide a more controlled environment where serial production is achievable. This decreases time, cost, and errors and maintains high quality. On the other hand, on-site assembly is much more unreliable.

3. Methodology

The research methodology is divided into two sections: the first one, Section A, investigates scientific literature, while the second one, Section B, investigates industrial literature, as performed by Mignacca and Locatelli (2020a) and Mignacca and Locatelli (2020b).

Section A has three main stages and is represented in the diagram in Fig. 1. The first stage is the identification of keywords relevant to the research objective. Several iterations led to the following list:

- *LFRs*: "Lead cooled reactor" and "LFR";
- *Economics*: "Cost", "Costs", "Economy" and "Economics";
- *Finance*: "Finance" and "Financing".

We selected the Scopus database because of its international coverage of major scientific peer-reviewed journals, books, and conference papers. In the second stage, a search string was developed with the

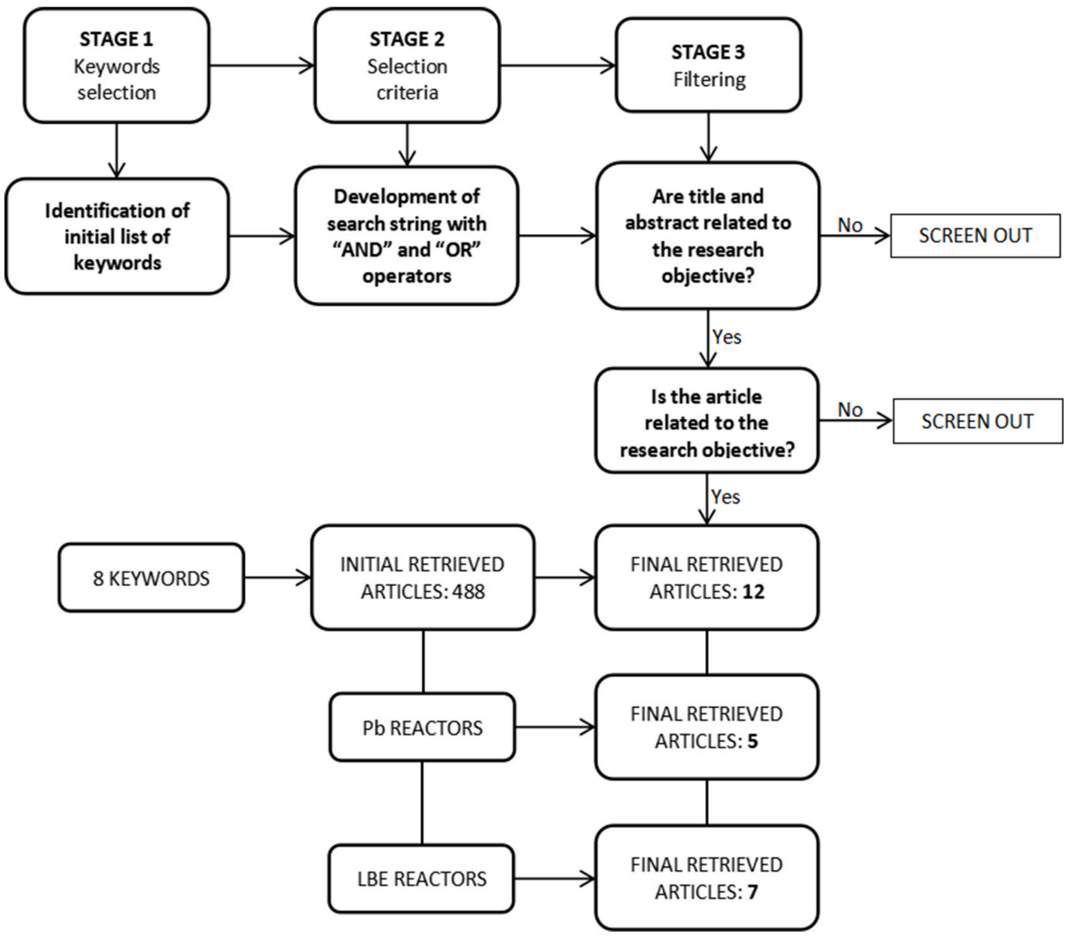

Fig. 1. Section A of the selection process, adapted from Mignacca and Locatelli (2020a) and Mignacca and Locatelli (2020b).

boolean operators "AND" and "OR", and used to search the relevant literature. The obtained string was: ("Lead cooled reactor" OR "LFR") AND ("Cost" OR "Costs" OR "Economy" OR "Economics" OR "Finance" OR "Financing")

The search was carried out on 23/02/2023 among the titles, keywords, and abstracts. We did not select a time frame (the default is 1966–2023), and we did not exclude any language, but all the non-English articles will be screened out in the third stage. From this selection step, we retrieved 488 articles.

The third filtering stage follows these steps:

- Carefully read the title and abstract of each article and assign to each of them a score from 0 to 2 depending on their relevance to the research objective ("0" as non-relevant, "1" as marginally relevant, and "2" as relevant). This technique was adapted from Sainati et al. (2017), Pittaway et al. (2004), and Di Maddaloni and Davis (2017). With this step, we screened out 455 articles, while the remaining 33 were marked with a "2" and are considered in the next step. Of these, 21 were related to reactors using Pb, while the remaining 12 considered LBE ones.

Table 2
LFR design in ARIS database, search date: 07/03/2023. Section B of the selection process.

Reactor	Coolant	Country	Does the ARIS report provide relevant data?	Design organization	Does the design organization's website provide relevant data?	Were other resources found on other websites?
ALFRED	Pb	EU	No	Ansaldo Nucleare	No	Yes
BREST-OD-300	Pb	Russia	No	RDIPE	No	Yes
CLEAR-I	LBE	China	No	INEST, Chinese Academy of Sciences	No	No
ELECTRA	Pb	Sweden	No	KTH	No	No
ELFR	Pb	EU	No	Ansaldo Nucleare	No	No
G4M	LBE	USA	No	Gen4 Energy Inc.	No	No
LFR-AS-200	Pb	Luxembourg	No	Hydromine Energy S.a.r.l	No	No
MYRRHA	LBE	Belgium	No	SCK-CEN	Yes	Yes
PEACER	LBE	Rep. of Korea	No	Seoul National University	No	No
SEALER	Pb	Sweden	Yes	LeadCold	No	Yes
SVBR-100	LBE	Russia	No	AKME Engineering	Yes	Yes
W-LFR	Pb	USA	Yes	Westinghouse Electric Company LLC	No	No

- Carefully read the entire articles, screening out the ones that turned out to be only marginally relevant to the research objective (because too qualitative and/or focused on different aspects). After this second step, 12 articles were left to be analyzed: 5 concerning Pb-cooled reactors and 7 concerning LBE-cooled ones.

In section B of the selection process, we investigated industrial literature. Initially, we examined the IAEA ARIS database (Advanced Reactors Information System, search date: 14/03/2023) (ARIS, 2021). Table 2 provides an overview of the reactor designs that were present at the time of the search (12 in total). For each of them, we consulted the ARIS report. Here, as for section A of the selection process, we considered only the ones mentioning a quantitative economic evaluation and/or financial analysis, while the others were screened out. ARIS (2019) and ARIS (2020) were the only two reports mentioning an economic evaluation for SEALER and W-LFR designs, respectively.

Additionally, for each design, we searched the design organization's website, looking for pages and documents related to the economic and financial aspects. The search was performed in the following way:

- *Ansaldo Nucleare.* The organization's website reports the different projects of interest under the voice "Offering". By selecting the voice "Nuclear", followed by "Innovation for future nuclear technologies" and "Generation IV" we can only find a qualitative description of the work of Ansaldo Nucleare about LFRs, not considered in this study.
- *RDIPE.* We were not able to find this organization's website.
- *INEST.* On the website menu, we can directly search for publications. All the ones retrieved for the reactor CLEAR-I do not mention any economic or financial aspects.
- *KTH.* The voice "Research" enables us to search using the keywords "SEALER" (8 results) and "LFR" (24 results). No result reported useful quantitative data about the economics and finance of LFRs.
- *Gen4 Energy Inc.* This company went out of business in 2018, and a website was not found.
- *Hydromine Energy s.a.r.l.* This company's website only gives a qualitative description of the projects performed.
- *SCK-CEN.* In the home page menu, we can select the voice "Expertises" which divides SCK-CEN work into six different areas. By selecting and reading the one regarding the MYRRHA reactor "Exploring innovative nuclear systems" we were able to retrieve SCK-CEN (2018). This is the only reference retrieved from this website.
- *Seoul National University.* On the home page of the website, we can directly find a search menu. However, no results were found by using the keywords and searching for "PEACER" and "LFR".
- *LeadCold.* On this website home page, we can find two different voices of interest. The first is "Technology" which leads only to a qualitative description of the SEALER-55 reactor. The second is "News" which reports only a limited number of online articles at the search time and none related to the research objective.
- *AKME Engineering.* In the menu, we can find the voice "Projects" which leads to a list of different projects including the SVBR-100 one with the title "Construction of a nuclear power plant with a capacity of 100 MWT" (AKME Engineering JSC, 2018).
- *Westinghouse Electric Company LLC.* Under the voice "Energy Systems" we can find "Lead-cooled Fast Reactors". This page however only gives qualitative indications of the economic advantages of LFRs.

Apart from the ARIS database and the already considered design organization websites, other ones were consulted, including GIF, NEWCLEO, ROSATOM, WNA, IAEA, and NEA. The following list indicates, for each website, the search procedure and the retrieved documents (if any):

- *GIF website* (search date: 16/03/2023). First of all, the latest annual report (of the year 2022) can be easily consulted directly from the home page. In this document, a lot of information is available for LFR technology and it is also mentioned that NEWCLEO is investing up to €50 million to build up a large-scale research infrastructure in collaboration with the ENEA research center in Brasimone (Italy) (GIF, 2023). However, quantitative data regarding the economic and finance of LFRs are not present and the report is screened out. In the home page menu, we can select the voices "Technology" and "Resources". In the former, we can find "LFR", leading to a page introducing the technology and the R&D in this topic around the world. We did not find any useful data on this page. Under "Resources" we can find the voice "Publications" which presents a list of documents that we thoroughly consulted. From this search emerged only publications related to the economic benefits of SMRs or Gen-IV technologies in general, often qualitative and not explicitly related to LFRs.
- *IAEA website* (search date: 16/03/2023). On the website home page, we can find "Resources", under which there is the voice "Scientific and technical publications". Once visited, we can select the "advanced search" to search for the listed topics. We looked at the results under the following ones: "Planning and economic studies section", "Design of nuclear power plants", "Nuclear Technology and Applications", "Energy", "Nuclear power reactors", "Research reactors", "Energy planning", and "Economics". Given the large number of publications, we first filtered them by simply considering the title alone. Publications not related to the research objective were discarded while the others were considered. With this search, we were able to retrieve 2 different reports: IAEA (2021) and IAEA (2022).
- *NEA website* (search date: 15/03/2023). On the website home page, we can find "News and resources" with over 4000 publications. We can select the topic of interest. We checked "Nuclear economics", which gave us 232 results at the search date. We searched through these publications using the following keywords: "LFR" gave zero results; "Lead" 20 results (all the retrieved publications were found here); "Economics" 8 results; "Finance" 4 results; and "GEN IV" 4 results as well. We found the following documents to be relevant to the research objective: NEA (2009) and NEA (2012). To these, we can also add the newly published NEA SMR dashboard (NEA, 2023).
- *NEWCLEO website* (search date: 15/03/2023). On the website home page, we can find "News & Insights" with 6 pages and a total of 24 online articles at the search date. Each of them was considered but no relevant data was found on this website.
- *ROSATOM website* (search date: 15/03/2023). In the home page menu, we can find the voice "News". Then, we can search through the numerous online articles present on the website. We used the following keywords: "LFR" (no results), "SVBR" (no results), and "BREST" (3 results from 2021). On this website, we were not able to retrieve data relevant to the research objective but we were able to find TASS (2021) mentioning ROSATOM by the Russian News Agency about the cost of the BREST fast reactor.
- *WNA website* (search date: 17/03/2023). On the home page of this website, we can find a search menu. Using the keyword "LFR" a total of 32 results were available. Out of these, the ones reporting relevant financial information for LFR designs were WNA (2020) and WNA (2021).

This search aimed at retrieving industrial reports and publications reporting a quantitative economic and/or financial analysis for any LFR design. Indeed, it was not limited to the reactor designs listed in the ARIS database. What follows is the list of LFRs for which we retrieved relevant data. Only a few reports are considered and this is because most of the ones reporting an economic or financial analysis resulted qualitative (e.g., describe how LFR may reduce the cost of the NPP thanks to their relatively high operating temperature and design simplification) and therefore were screened out:

- ALFRED (WNA, 2020);
- BREST-OD-300 (TASS, 2021; WNA, 2021);
- MYRRHA (NEA, 2009; NEA, 2012; WNA, 2020);
- SEALER (IAEA, 2021; NEA, 2023);
- SVBR-100 (WNA 2021; IAEA, 2022).

Note that we did not find any documents regarding reactor designs not mentioned in ARIS, such as CLFR, BLESS, LFR-AS-200, and all the other ones mentioned in Alemberti (2021). This is probably because their design development has not reached a detailed level as the ones reported, or because an economic evaluation or financial analysis has not been performed yet for such reactors. The last column of Table 2 indicates if any resources were found for the specific LFR. In total, from section B, we retrieved 12 additional documents.

In this work, we computed all the exchange rates between different currencies as a yearly average using the CambioEuro website (e.g., the exchange rate between the British pound and the American dollar in 2019 is the average value of all the available exchange rates between 1/1/2019 and 31/12/2019).

4. Summarizing the state-of-the-art in economics and finance for LFR technology

4.1. Scientific literature

We are going to present the articles we retrieved from section A of the selection process. They are divided into Pb-cooled reactors and LBE-cooled ones.

4.1.1. Lead-cooled reactors

We retrieved 5 articles about Pb-cooled reactors.

Ciotti et al. (2014) define LFR sustainability as having three different constituents: social, environmental, and economic sustainability. The third one introduces the main sources of economic uncertainty before considering in more detail the LEADER Project, which started in 2010 and concluded in 2013 (CORDIS, 2013). It had two main goals: the conceptual design of an industrial-size LFR (the so-called European LFR or ELFR) and the conceptual design of a scaled-down facility, the demonstrator ALFRED. The main results of this project can be found in (CORDIS, 2013), and to this day, the ALFRED reactor is planned to be built in Romania in the next years (Alemberti, 2021; WNA, 2020). Ciotti et al. (2014) perform a top-down cost evaluation with a Gen-III NPP as a reference, the article does not specify the reactor type but its electrical output is 1100 MWe. This assumption, though well presented by the authors, could be criticized because of the important differences between LFR and typical Gen-III technologies. We should acknowledge the increased complexity and design choices caused by the different coolant. If we consider a LWR as a Gen-III representative, on one side we have a water-cooled, moderated, typically large reactor, working at high coolant pressure; on the other, we have a fast reactor, cooled by heavy metals, behaving very differently against structural materials, at atmospheric pressure. In the article, the overnight construction cost was estimated at 4100 €/kWe (5447 $/kWe considering 2014 dollars). This value comprehends all the costs up to the start-up of the plant i.e., civil and structural costs, cost of mechanical equipment supply and installation, cost of electrical supply, instrumentation and control (I&C) systems supply and installation, project indirect costs (e.g., site supervision), and owner's costs (e.g., development and interconnection costs). A broader range was determined via a sensitivity analysis obtaining lower and upper bounds of 3600 and 4900 €/kWe, respectively (4783–6510 $/kWe). The energy generation cost was computed considering O&M and fuel cycle costs, and the range 0.0225–0.0690 €/kWh was obtained, with a reference value of 0.0375 €/kWh (0.0299–0.0917 and 0.0498 $/kWh, respectively). Ciotti et al. (2014) affirm the cost estimation for the 600 MWe ELFR is 10% higher than a same-size Gen-III plant. Operation easiness and intrinsic safety could reduce the costs for future projects. Electricity generation can vary a lot on the geographical position of the plant. Indeed, the authors report that the median nuclear electricity cost is 0.030 $/kWh for Asian countries, but raises to 0.050 $/kWh and 0.060 $/kWh for American and European ones respectively.

Li et al. (2018) perform the calculations for the total investment for a miniaturized hypothetical LFR, coupled with a supercritical CO_2 (sCO_2) recompression cycle. Table 3 summarizes the main data and assumptions of the article.

Li et al. (2018) consider a very small, 10 MWe reactor. To compute the total investment, the authors calculate the investment costs of the key components, i.e., heat exchangers, compressors, turbines, and the core. They do not compute pipeline costs because they represent only a small portion of the total. The cost of the turbine is determined by the power output while for the heat exchangers by the surface area. These values are then summed up and added to the reactor investment accounting also for inflation. The final total investment is $36.5 million, or 3654.2 $/kWe which corresponds to an electricity cost of 0.0536 $/kWh. Li et al. (2018) affirm this value is less than the 2013 Chinese electricity price for the nuclear industry (0.0632 $/kWh). We can say the authors considered the total investment as just the sum of the costs of the main equipment without taking into account other costs (e.g., civil and structural costs, indirect costs, etc.). They did, however, take into account time inflation. Indeed, the article continues with the investment analysis computing a yearly payment to the bank of $2.9 million while the benefit of the system every year is estimated at $4.0 million. Their difference, $1.1 million, leads to a payback time of 34.1 years, which is less than the operating life of the plant, and a company final profit of $6.3 million.

Li et al. (2019) consider again a hypothetical 10 MWe LFR. It focuses on the performance comparison of five different sCO_2 power cycles. This study is performed via sensitivity analysis considering variations in the inlet temperature of the turbine and the main compressor, the total thermal conductivity of the regenerator, and the maximum pressure of the cycle. Li et al. (2019) conclude the recompression cycle is the optimal choice for the 10 MWe LFR: the thermal efficiency of the plant ranges from 36.68% to 44.46%, with an electricity production cost between 0.050 and 0.055 $/kWh. Interestingly, the authors provide the full cost statement of the 10 MWe LFR integrating the sCO_2 cycle with optimal operating parameters. The statement includes values for the costs of land and the main buildings, the detailed costs for the different plant equipment, electrical and I&C components, furniture, and fixtures. The sum of values gives a total direct cost of $16.8 million. The cost statement also provides values for the costs of construction services, engineering management, site supervision, on-site office services, and owner's ones. These values are all summed under the total indirect cost voice totalling $5.0 million. The total infrastructure cost reported by Li et al. (2019) is the sum of the direct and indirect values, therefore $21.8 million. However, the authors also consider an incident total cost of $3.5 million and an interest during construction of $2.7 million. The total investment cost is then reported to be around $28.0 million (or 2798.9 $/kWe).

Soto et al. (2022) consider a Westinghouse LFR, 950 MWt, and 450 MWe. The pre-conceptual design for the W-LFR was completed in 2017

Table 3
Main data and assumptions presented by Li et al. (2018).

Data	Value
Electric power	10 MWe
Bank interest rate	5%
Loan repaying time	20 years
Yearly operating time	7500 h (85%)
Reactor core investment	$5 million
Running period	40 years

and the start of the construction for a full-scale prototype is expected for 2030 (ARIS, 2020). In this article it is analyzed in a coupled configuration with a Thermal Energy Storage (TES), to improve its operating flexibility. Adding TES to an existing NPP would require oversizing the turbine, the generator, and the supporting subsystems, therefore, it increases capital cost. TES is assumed to be a two-tank storage system with molten salts as thermal fluid and its energy capacity is measured in equivalent hours of nominal turbine operations. Soto et al. (2022) made a few assumptions: the LFR can alter its thermal power in a relatively fast time, a Rankine cycle design is present for the secondary circuit, and perfect price forecasting is performed. For the last assumption, two separate tariff rates are considered: a generic peak prizing schedule from the System Advisor Model (SAM) provided by the National Renewable Energy Laboratory of Colorado (USA), and a normalized prizing time series from the California Independent System Operator market (CAISO, data from 2019). The tariffs are normalized to 8760 over a full year (hourly average of 1). However, for the SAM, other two scenarios are added reaching a total of four: peaks (tariff rate higher than 1) are multiplied by 1.5 and 2.0 while valleys (tariff rate lower than 1) are divided by the same values. For each scenario, the best case regarding the electricity production cost is investigated by varying both the turbine and TES sizes. The estimations performed by Soto et al. (2022) are based on an estimate of the reactor cost of 4150 $/kWe which is reported by the authors as "Westinghouse estimates". Since the article concerns the electricity price computation, we may deduce the reported value represents an estimation of the total capital investment, considering both direct and indirect construction costs and interest rates. Table 4. shows the results from Soto et al. (2022). The authors also performed a sensitivity analysis considering the increase and decrease of TES cost (leading to worse and better electricity prices, as expected), and performance penalties incurred by implementing TES.

Concluding articles related to Pb-cooled reactors, Du et al. (2022) perform a multi-goal optimization considering the size and thermo-economic performance of a hypothetical LFR. The authors assume 8000 annual operating hours, a fuel cost of 0.0074 $/kWh, and O&M costs equal to 6% of the capital one. The authors introduce the "capital cost of the system": the sum of the costs of the reactor, the turbine, the compressor, the pump, and the different heat exchangers. The article does not provide an explicit value for this capital cost, however, we may say this value comprehends the cost of the equipment but does not consider the other ones. Du et al. (2022) focus more on the optimization problem, indeed, the authors compute the Pareto optimal solutions in the following four cases (in parenthesis we reported the optimal points in each case):

- Optimization of LCOE and thermal efficiency (0.05560 $/kWh and 43.45% respectively);
- Optimization of total volume and thermal efficiency (4.20 m^3 and 42.17% respectively);
- Optimization of LCOE and total volume (0.05692 $/kWh and 3.71 m^3);
- Optimization of all three quantities (obtaining 4.43 m^3 for the total volume, 42.14% for thermal efficiency, and an LCOE of 0.05630 $/kWh).

4.1.2. LBE-cooled reactors

We retrieved 7 articles about LBE-cooled reactors.

Mikityuk et al. (2002) consider the RBEC-M fast reactor, a 900 MWt (340 MWe) developed in Russia from the late 1980s onward. Currently, there are no reactors under construction or planned with this design (IAEA, 2023). The total RBEC-M cost is considered as the sum of two contributions: the reactor module cost and the one for the nuclear steam supply system (NSSS). Mikityuk et al. (2002) assume the NSSS fraction corresponds to 25% of the total cost. The authors used data from other two Russian reactors, VVER-1000 and BN-600, to estimate the materials mass and cost parameters of RBEC-M NSSS. This assumption by the authors could be criticized because of the important differences among the designs of the LFR, the much larger water-cooled VVER-1000, and the sodium-cooled BN-600. However, we can say that, like the BN reactors, the RBEC-M also has an intermediate circuit. In the article, the reactor module mass and its specific cost are assumed to be equal to the BN-600 ones. The specific capital cost estimate turned out to be 1670–1750 $/kWe. Since the estimations are performed by evaluating material quantities we can deduce the values reported refer to the overnight direct costs without considering indirect and owner's costs. The authors add that serial manufacture and multi-unit NPP construction could decrease this value by 15–25%. They conclude affirming the assumed cost estimate for LBE (30–40 $/kg) led RBEC-M NSSS specific cost to be 25–35% higher than the similar value for VVER-1000.

Davis et al. (2002) focus on a hypothetical 1040 MWt and 350 MWe reactor that aims at producing low-cost electricity and burning actinides. This pool-type reactor uses a conventional steam power conversion cycle and a mixture of plutonium, actinides, and zirconium as fuel. The estimation of the capital cost for the considered reactor is based on a comparison with the Advance Liquid Metal Reactor (ALMR). Although acknowledged by the authors, the ALMR has a quite different, and perhaps more complex, design from the considered LFR. Indeed, it utilizes sodium as a primary coolant and has an intermediate heat transport loop. Table 5 summarizes the main assumptions for this estimation.

The preliminary estimation for the capital cost is 4300 $/kWe, in 1999 dollars, corresponding to 0.049 $/kWh. This value is not the overnight construction cost, but an estimation of the total capital cost considering also the interest during construction and time inflation. Davis et al. (2002) also perform a sensitivity analysis of single key parameter variations. Table 6 reports the parameters considered and the ranges in which they vary from the value giving the minimum cost to the value giving the maximum one.

Hejzlar et al. (2004) consider a hypothetical 700 MWt (300 MWe) reactor, for which they provide a design for the primary system and the balance-of-plant. The total capital cost assessment is performed by comparison with an ALMR reference plant. As mentioned by Davis et al. (2002), it is sodium-cooled, with an intermediate loop, and a Rankine cycle on the secondary side, giving it a quite different design from the LFR. The calculations comprehend both FOAK and NOAK plants with one or three reactor modules (FOAK-3 and NOAK-3, total electrical power output of 900 MWe). This value summarizes the overnight construction costs, the interest contribution but also the effect of inflation, assumed at 1.80% per year. Table 7 reports the results. The first row represents the specific capital cost for a plant with a Rankine power cycle. Hejzlar et al. (2004) perform a sensitivity analysis considering a

Table 4
Optimal plant designs and the corresponding electricity prices (Soto et al., 2022).

Market Scenario	Turbine size [MWe]	TES size [h]	Electricity Price [$/kWh]
SAM peaks	450	0	0.0654
SAM peaks x 1.5	600	2	0.0649
SAM peaks x 2.0	700	5	0.0626
CAISO	750	5	0.0563

Table 5
Main assumptions in capital cost estimation in Davis et al. (2002).

Parameter	Value
Construction time	5 years
System Lifetime	60 years
Plant type	FOAK
Cost of money	11.35%
Inflation rate	5% per year
State and federal tax rate	36.63% per year

Table 6
Sensitivity analysis conducted by Davis et al. (2002).

Parameter	Variation	Cost range [$/kWe]
Superheating degree	0 → 100 K	No significant variations
Secondary pressure	70 → 150 bar	4300 → 4730
Chimney height	15 → 8 m	4130 → 4515
Capacity factor	90 → 70 %	3870 → 4840
Construction period	3 → 7 years	4000 → 4600

Table 7
Specific capital cost estimations for the different Balance of Plant (BOP) and configurations in Hejzlar et al. (2004). All values expressed in [$/kWe] in 2002 dollars.

BOP	FOAK-1 300 MWe	FOAK-3 900 MWe	NOAK-1 300 MWe	NOAK-3 900 MWe
Rankine	2540	1993	1932	1657
sCO_2 50%	2154	1569	1647	1279
sCO_2 25%	1960	1357	1493	1099

sCO_2 cycle, less expensive than a Rankine one, with the assumption that the cost of the former is 50% or 25% of the latter (respectively sCO_2 50% and sCO_2 25%).

The same 300 MWe reactor is considered also by Hejzlar and Davis (2004) in which the potential benefits of thorium-base fuel are explored. In particular, the capital cost for a FOAK is assumed as 2154 $/kWe, a value which can be seen in Table 7, leading to an electricity price of 0.030 $/kWh. The article concludes the introduction of thorium fuel is not beneficial because, though it increases the capacity factor of the plant improving electricity cost by 0.0013 $/kWh, it must come with an additional uranium separation step which has a larger negative impact on electricity cost of 0.002 $/kWh.

Chikazawa et al. (2005) studied a hypothetical small natural convection LBE-cooled reactor, that can operate without refueling for 30 years, with an electrical output of 50 MWe. The total cost is the sum of the direct and indirect costs. The direct one, for each main component, is evaluated as the material unit cost multiplied by the material mass. The indirect costs comprehend the field, engineering, owner's costs, and interest during construction. Chikazawa et al. (2005) evaluate a cost of around 10,000 $/kWe which translates into an electricity cost of 0.100 $/kWh. The authors affirm this value is too high for the power source of a city connected to a power grid, however, it is still attractive for remote regions such as Alaska and Hawaii where in 2001 the electricity price was reported to be 0.059–0.360 $/kWh.

Wider et al. (2005) propose a design for a 600 MWe LFR. In describing the advantages of LFRs regarding economics, safety, and proliferation resistance, it introduces the Russian LBE-cooled SVBR-100. This NPP comprehends 2 units of 16 reactors each. The single reactor can produce 102 MWe. The specific total capital investment for the construction is reported to be 661.5 $/kWe for a produced electricity cost of 0.0146 $/kWh. Wider et al. (2005) report 1991 dollars and affirm the low values reflect the low wages and costs in Russia in the early 1990s. Currently, this reactor technology is in the detailed design phase for potential construction starting in 2025 (IAEA, 2022).

Lastly, Cho et al. (2015) perform a detailed study concerning hypothetical, land-transportable, fully passive LBE-cooled SMRs. They report the estimation for the overnight capital cost (direct and indirect construction costs, without considering interest during construction and inflation) and the LUEC for different reactor sizes. Note that the authors compute the overnight capital cost for the plant but will introduce an interest rate to compute the electricity price. Table 8 reports the main assumptions, common to all sizes.

Cho et al. (2015) introduce the scaling factor n to account for the penalty from economy-of-scale, and the discount rate r. The estimated overnight capital costs can be found in Table 9. It is clear that, because of

Table 8
Main parameters and assumptions common to all SMRs in Cho et al. (2015).

Parameter	Value
Construction period	3 years
Plant lifetime	60 years
Availability	85%
Reference reactor	APR-1400
Simplification factor	0.85

the economy-of-scale, the specific costs tend to exponentially increase as the size of the reactor diminishes. For what concerns the LUEC value, Cho et al. (2015) derive a lower bound curve, considering $n = 0.7$, $r =$ 5%, and O&M and fuel cost of 0.0071 $/kWh, and an upper bound one, with $n = 0.5$, $r =$ 10%, and O&M and fuel cost of 0.0362 $/kWh. Both curves decrease if the electricity generation increases. If the SMR size is 5 MWe, the LUEC upper bound is 0.275 $/kWh, the average is 0.180 $/kWh, and the lower bound is 0.085 $/kWh. If the SMR size is 100 MWe, LUEC is generally lower: the upper bound is 0.090 $/kWh, the average is 0.060 $/kWh, and the lower bound is 0.030 $/kWh. Table 9 also reports the estimations for the investment component of LUEC. To obtain the total value we should consider also the O&M, fuel, carbon tax, and decommissioning components (Cho et al., 2015).

4.2. Industrial literature

From section B of the selection process, we retrieved 12 different documents.

Only two reports in the ARIS database mentioned the economic aspects of the considered reactor. ARIS (2020), presenting the W-LFR, mentions a materials and equipment overnight capital cost lower than $1380 million, 3000 $/kWe, for a NOAK, construction time of 36 months (in 2015 dollars). ARIS (2019) performs a more detailed estimation for the SEALER reactor: the total overnight capital cost (not only materials and equipment) of a 4 × 55 MWe NPP is estimated at £400 million ($510 million in 2019 dollars, 2318 $/kWe) based on the assumption that the primary system is manufactured in a factory where automated procedures are applied. The lifetime LCOE for the same reactor is estimated at 50 £/MWh (equivalent to 0.0638 $/kWh), with the assumptions of a 6% interest rate, a lifetime of 25 years, and a capacity factor of 90%. Since a single SEALER fuel load is estimated to last 25 years, an equivalent fuel cost is computed at 12 £/MWh (0.0153 $/kWh), but may alternatively be included in the capital cost at an expense of £170 million ($217 million), while O&M and D&D costs are estimated at 17 £/MWh (0.0217 $/kWh).

Directly on the websites of the design organizations in ARIS, it is possible to find an economic estimation only for SVBR-100 from AKME Engineering (AKME Engineering JSC, 2018). It is reported its construction is a 36 billion RUB project ($574 million in 2018 dollars). On the SCK-CEN website (SCK-CEN, 2018), it is reported the Government of Belgium financed €558 million of the total MYRRHA project budget of €1.6 billion in 2018 (in 2018 dollars, $659 million of the total $1.89 billion).

At last, we conclude with the remaining 8 documents we found consulting the most important agencies, companies, and group websites in the nuclear sector. They pertain to some of the LFR designs reported in ARIS. What was found is the following:

- *ALFRED*. A consortium known as FALCON was set up in 2013. The total cost was put at around €1.0 billion ($1.22 billion in 2020 dollars) and the construction site of choice is in Mioveni, Romania (WNA, 2020).
- *BREST-OD-300*, whose construction cost was reported to be 100 billion RUB ($1.36 billion considering 2021 dollars, 4530 $/kWe) by ROSATOM (TASS, 2021). WNA (2021) reports that, in 2018,

Table 9
Overnight capital cost and investment component of LUEC from Cho et al. (2015). The size of the reactor varies from 5 MWe to 100 MWe.

		SMR-5		SMR-40		SMR-80		SMR-100	
Overnight capital cost [M$]	*n* = 0.5	108.4		306.5		433.5		484.7	
	n = 0.6	61.9		215.7		327.0		373.8	
	n = 0.7	35.4		151.8		246.6		288.3	
Interest rates		*r* = 5%	*r* = 10%	*r* = 5%	*r* = 10%	*r* = 5%	*r* = 10%	*r* = 5%	*r* = 10%
Investment component of LUEC [$/kWh]	*n* = 0.5	0.140	0.242	0.049	0.086	0.035	0.061	0.031	0.054
	n = 0.6	0.080	0.138	0.035	0.060	0.026	0.046	0.024	0.042
	n = 0.7	0.046	0.079	0.024	0.042	0.020	0.034	0.019	0.032

ROSATOM asked the Russian Government to allocate an additional RUB 200 billion ($3.05 billion) over the following 6 years under the federal target program for nuclear power. It is also reported that the BREST project had a total funding of RUB 140 billion ($3.1 billion) for the 2010–2020 period. WNA (2021) also states that, in 2010, a Russian Government decree approved RUB 40 billion ($1.3 billion) funding for an initial 300 MWe BREST unit.

- *MYRRHA.* NEA (2009) reports a total capital cost of €960 million ($1.34 billion, 2009 dollars), reduced to €650 million ($906 million) considering only the 100 MWt reactor without the accelerator system. The total cost already contains €193 million for contingency ($269 million), which is 20%, although, for such innovative projects, it is usually around 30–35%. NEA (2009) also estimates the operating costs of MYRRHA at around €61 million ($85.1 million) per year. They should be completely recovered as reported in Table 10. Moreover, NEA (2012) reports that in 2010 the Belgian Government decided to provide a subsidy of €60 million ($79.5 million) for the first detailed design phase of the project. Throughout 2011 the project has advanced according to schedule. WNA (2020) also reports that Belgium's SCK-CEN will provide a total of €560 million ($681 million in 2020 dollars).
- *SEALER.* IAEA (2021) reports the specific cost of staffing a small NPP such as the 220 MWe SEALER-UK is likely to be higher than a conventional light water plant simply because there is the need for a minimum amount of security staff which cannot be reduced further. To compensate for the increase, the primary system should be built by automated procedures in a serial manner. As can be seen in Table 11, IAEA (2021) affirms the LCOE is 0.0757 $/kWh, under the conditions of two years construction period and a production of 200 units during its economic life, corresponding to a total of 11 GWe (which probably would need the identification of export markets). As of 2023, NEA released the first edition of the SMR dashboard (NEA, 2023) in which SEALER is considered. Multiple funding announcements are reported (the 2023 SEK-USD exchange rate, in this case, is the average value of the exchange rates from 1/1/2023 to 14/4/2023) including 99 million SEK from the Swedish Energy Agency (equivalent to $9.5 million), 25 million SEK ($2.4 million) by Norrsken, and 1.7 million SEK ($0.16 million) award through Eurostars. Additionally, LeadCold has an agreement with the utility NewClearEnergy, where a percentage of the electricity sales will be used to finance the design and safety analysis of SEALER.

Table 10
Estimated revenues of the MYRRHA NPP (NEA, 2009) in 2009 dollars.

Source of revenue	[M€/y]	[M$/y]
Owners' consortium	25.3	35.3
R&D services (from SCK-CEN)	2.5	3.5
R&D services (from other partners)	14.6	20.4
International programs R&D support	10.0	13.9
Manufacture of radioisotopes	2.2	3.1
Doping of silicon	4.5	6.2
Other industrial services	1.0	1.4
Consultancy and training	1.0	1.4
Total estimated revenues	61.1	85.2
Estimated operational costs	61.0	85.1

Table 11
Target economic indicators of SEALER-UK (IAEA, 2021) in 2021 dollars.

Item	Value
Number of units	4
Power per unit	55 MWe (220 MWe total)
Overnight cost per unit	£140 million ($193 million)
Specific overnight cost	2500 £/kWe (3440 $/kWe)
Construction period	2 years
Cost of capital	9%
Operational costs	20 £/MWh (0.0275 $/kWh)
Cost of electricity	55 £/MWh (0.0757 $/kWh)

- *SVBR-100.* WNA (2021) reports that, in 2010, the Russian Government allocated RUB 13.23 billion, including RUB 3.75 billion from the federal budget. However, in 2014 ROSATOM reported that the cost escalated to RUB 36 billion ($550 million), more than double the original estimate, making the project "less commercially attractive". IAEA (2022) reports that, for the FOAK pilot plant, the expected total construction cost is around 6000 $/kWe for a LCOE of 0.100 $/kWh. However, for a NOAK plant consisting of 4 reactor facilities, these values are expected to decrease to 3000 $/kWe and 0.060 $/kWh.

4.3. Summary and comparison

Given the large amount of heterogeneous information, we decided, before summarizing the retrieved economic and financial data, to provide concisely in Table 12 what type of information is available in each document we considered.

It is now possible to enter the details of the information the references provide. Table 13 summarizes the economic data we retrieved. Each of them is adjusted for inflation considering 2023 dollars. It is important to mention the following notes:

- *A*, for references having one or more ranges of values always the smallest and largest are considered.
- *B*, for references performing optimization studies only the best solution (or range of best solutions) is reported for simplicity.
- *C*, for the MYRRHA reactor, the thermal energy is considered (100 MWt) as well as the total investment (reactor and accelerator system).

Table 13 provides an overview of how the information is distributed among the documents. While some perform a more detailed study, others simply mention the value here reported. It is interesting how documents about Pb and LBE reactors seem temporally divided. Literature in the early 2000s was primarily focused on LBE technology while in the last decade, the interest shifted towards Pb. In Figs. 2 and 3, we can see the different values for specific capital cost and LCOE respectively, for both reactor types. The diversity and dispersion of these estimates underscore the heterogeneity of the different references, as can be seen in Table 12. Indeed, it is challenging to achieve a precise economic estimation (or at least a reasonable range of value) and, considering the reported values, they can even vary by an order of magnitude. Additionally, in Table 13 and Fig. 2, we reported the overnight capital

Table 12
The different types of information provided in each of the considered documents, 24 in total.

Reference	Type of reactor	*Capital cost*				Cost of electricity	Financial information or revenue estimation
		Equipment capital cost	Overnight direct capital cost	Overnight capital cost	Total capital investment		
Davis et al. (2002)	LBE				X	X	
Mikityuk et al. (2002)	LBE		X				
Hejzlar et al. (2004)	LBE				X		
Hejzlar and Davis (2004)	LBE				X	X	
Wider et al. (2005)	LBE				X	X	
Chikazawa et al. (2005)	LBE				X	X	
NEA (2009)	LBE				X		X
NEA (2012)	LBE						X
Ciotti et al. (2014)	Pb			X		X	
Cho et al. (2015)	LBE			X		X	
Li et al. (2018)	Pb	X				X	X
AKME Engineering JSC (2018)	LBE				X		
SCK-CEN (2018)	LBE						X
Li et al. (2019)	Pb				X	X	
ARIS (2019)	Pb			X		X	
ARIS (2020)	Pb	X					
WNA (2020)	Pb, LBE						X
WNA (2021)	Pb, LBE						X
TASS (2021)	Pb				X		
IAEA (2021)	Pb			X		X	
IAEA (2022)	LBE				X	X	
Du et al. (2022)	Pb	X				X	
Soto et al. (2022)	Pb				X	X	
NEA (2023)	Pb						X

Table 13
Summary of all the economic data in the retrieved documents and overnight capital cost from the reactors data present in Lovering et al. (2016), mostly LWR. Values are corrected for the current year (2023).

REFERENCE	Notes	LEAD		LBE	
		Capital	Electricity	Capital	Electricity
		[$/kWe]	*[$/MWh]*	*[$/kWe]*	*[$/MWh]*
Davis et al. (2002)	A	–	–	6966–8712	88.2
Mikityuk et al. (2002)		–	–	2783–2917	–
Hejzlar et al. (2004)	A	–	–	1832–4233	–
Hejzlar and Davis (2004)		–	–	3590	50.0
Wider et al. (2005)		–	–	1464	30.9
Chikazawa et al. (2005)		–	–	~15400	~154.0
NEA (2009)	C	–	–	18700	–
Ciotti et al. (2014)		6063–8252	37.9–116.2	–	–
Cho et al. (2015)	A	–	–	3655–27482	38.0–348.6
Li et al. (2018)		4356	63.9	–	–
AKME Engineering JSC (2018)		–	–	6710	–
Li et al. (2019)		3326	59.6–65.6	–	–
ARIS (2019)		2727	75.1	–	–
ARIS (2020)		<3803	–	–	–
TASS (2021)		5005	–	–	–
IAEA (2021)		3800	83.6	–	–
IAEA (2022)		–	–	3069–6137	61.4–102.3
Du et al. (2022)	B	–	56.9–58.2	–	–
Soto et al. (2022)	B	4245	57.6–66.9	–	–
Overnight capital costs from Lovering et al. (2016)	USA France	690–15175 1517–3449			

cost historical values of the reactors built in the USA and in France retrieved from Lovering et al. (2016). This article reports values from the early 1950s demonstration reactors up to the 2010 ones, and most of the values are for LWR. The USA range is affected by the Three Mile Island accident. It caused the specific overnight construction cost to increase 2 ÷ 4 times for the reactor being built in that period (Lovering et al., 2016). We expect a LFR to be more expensive than the more common LWR, especially for FOAK and smaller plants. In most cases, the values reported in the literature are comparable or slightly higher than the cost range seen in France and fall in the lower part of the USA range. However, over the past few decades, especially Asian countries greatly improved their expertise in building NPPs on time and within budget (WNA, 2023). This is not the case e.g., for Europe and the USA, leading to notable disparities between these regions of the world regarding the cost of building the reactor and its electricity price (Lovering et al., 2016; Ciotti et al., 2014).

Concerning the LCOE of PWR, we can examine the case of France. According to Boccard (2014), the “past” nuclear electricity in France

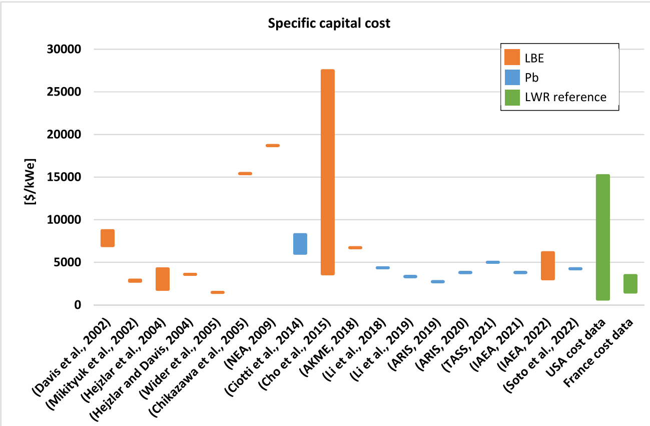

Fig. 2. Specific capital cost comparison.

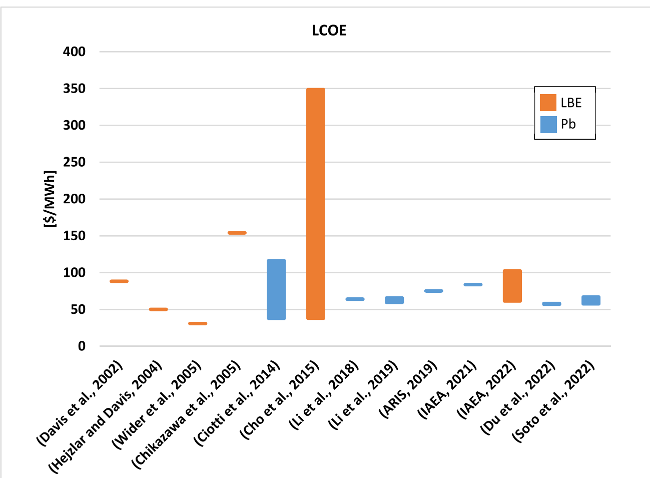

Fig. 3. LCOE comparison.

was at best as cheap as the observed market price of Europe (60 €/MWh or 78 $/MWh in 2012 dollars) but may become a third more expensive. In 2012, the French Government set the nuclear electricity tariff at 42 €/MWh, as the forecasted cost of running the nuclear plant fleet was 39 €/MWh (54 and 50 $/MWh) for the subsequent 15 years. Boccard (2014) confronted this value with its tentative assessment for future nuclear power between 76 and 117 €/MWh (99 and 152 $/MWh in 2012 dollars). When escalated considering the inflation between 2012 and 2023, this value is comparable to the ones reported in most cases for LFRs in literature. Indeed, many estimations are driven by the comparison with other (typically large) reactors, and by the assumptions made by the different authors which often include design simplification and high efficiency leading to an overall cost reduction.

It is also worth mentioning that this process of raising costs with general inflation is not always sufficient. Especially in the nuclear sector, some components might have a higher cost increase than the one expected from inflation by itself, e.g., because of higher safety requirements. A possible solution to this issue is looking at the global changes in costs for NPPs and addressing the historical variation in the country hosting the LFR of interest. Lovering et al. (2016) report the historical data on the overnight construction cost for NPP (until 2010). Depending on the country, we can have a trend "against" inflation (e.g., South Korea), a cost increase compatible (e.g., France), or much higher than inflation (e.g., USA). After the Fukushima nuclear accident, in some countries, the cost of nuclear was expected to rise (Boccard, 2014), some went for a nuclear phase-out while in others, especially in Asia, the nuclear expertise improved and reduced the overall costs (Ciotti et al., 2014). For simplicity, these complex, usually country-dependent scenarios are not implemented in this analysis. Indeed, we considered solely a general inflation increase.

On the financial side, Table 14 summarizes the information we retrieved for both reactor types. The number of references is very low (only 7). Concerning LBE reactors, we found data about MYRRHA and the Russian SVBR. For Pb reactors, only 4 documents reported relevant data: Li et al. (2018) give some estimations for the company profit for a hypothetical 10 MWe (40 years life span) reactor; WNA (2020) and WNA (2021) give information about ALFRED and BREST designs; and NEA (2023) reports the actual public investment announcements for the SEALER-UK reactor. It is entirely missing a description of viable financial models for LFRs. The main knowledge gaps on the financial side are further described in the next section.

5. Knowledge gaps and further research

Economics. Most of the retrieved documents discussed, or at least mentioned, an economic evaluation for a certain LFR. Regardless, we identified four main knowledge gaps.

- *Licensing process.* This process is, by itself, usually lengthy and costly, even for conventional LWRs. Moreover, it becomes increasingly uncertain if the reactor design deviates from this technology. It would be beneficial to acquire more information about the different steps of the licensing process for the LFR, such as how much they cost and how long they take. Moreover, this information may vary significantly between two different countries.
- *Cost breakdown.* In most cases, the cost breakdown for the total capital investments is not provided. These values include important aspects of the project lifecycle, such as engineering, development, permits, etc. Typical values for activities breakdown for large Gen-III LWRs are the following: 12% design, architecture, project

Table 14
Summary of the financial data in the retrieved documents. All values are corrected to the current year (2023).

REFERENCE	Reactor	Summary
NEA (2009)	LBE - MYRRHA - 100 MWt	Estimate yearly revenues at a total corresponding to $119 million which can cover operational costs.
NEA (2012)	LBE - MYRRHA - 100 MWt	The government of Belgium financed the first detailed design phase for a total corresponding to $109 million.
Li et al. (2018)	Pb - 10 MWe	Computation of yearly profit and payment to the bank ($4.8 and $3.5 million respectively). Payback time of 34.1 years and final profit of $7.5 million.
SCK-CEN (2018)	LBE - MYRRHA - 100 MWt	The government of Belgium financed one-third of the MYRRHA project budget for a total corresponding to $785 million.
WNA (2020)	Pb - ALFRED - 100 MWe	The total cost of the ALFRED project was put up to what corresponds to $1.41 billion.
	LBE - MYRRHA - 100 MWt	For the MYRRHA project, SCK-CEN will provide what corresponds to $787 million.
WNA (2021)	Pb - BREST - 300 MWe	The total resources allocated for the BREST technology now would correspond to $4.21 billion. In 2010, the Russian Government approved a total funding corresponding to $1.79 billion for the development of the first 300 MWe BREST unit.
	LBE - SVBR - 100 MWe	SVBR costs escalated to what now corresponds to $696 million.
NEA (2023)	Pb - SEALER - 220 MWe	Different funding announcements for SEALER-UK: Swedish Energy Agency ($9.5 million), Norrsken ($2.4 million), and Eurostars ($0.16 million). Agreement with NewClearEnergy: a percentage of the electricity sales will finance design and safety analysis.

engineering, and management; 28% nuclear island; 15% conventional island; 18% balance of plant; 22% civil works and transportation; 5% commissioning. Alternatively, it is possible to perform the same breakdown in terms of labor, goods, and materials: 48% equipment; 12% construction materials; 25% labor onsite; 10% project management services; and 5% first fuel load and other services (WNA, 2022). These values may vary for LFRs due to their significant differences from LWRs considering the technology, the scale of the plant, and the supply chain.

- *Fuel cost and waste.* Since LFR may be used to burn actinides from other reactors' spent fuel, it is important to study in detail the fuel cost for LFRs. In particular, some questions arise: how much does it cost to process the LWR spent fuel to separate the actinides? And to fabricate the LFR fuel? How much actinides mass is necessary to load the fuel? Is the process repeatable or will it eventually end due to actinides shortage? Since LFR in this configuration will use non-standard fuel with few suppliers, is it more convenient to implement a standard fuel cycle or to approach the burning process? How will waste management be affected?
- *Estimations.* Having read the considered documents, we may ask ourselves whether the performed estimations are clear in the way they are computed, if they are based on rightful assumptions or too strong or controversial ones, caused by the lack of data. Some of the estimations are obtained by confronting the LFR with reference NPPs, which may be different in design and technology. Others omit important aspects or hypotheses useful to better understand what was being computed. It would be useful to understand what assumptions may or may not be made. Building a prototype should be the best way to have additional insights for a real LFR.

Financing. Few documents mentioned the financial aspects of LFRs. Large gaps appear because most of the literature focuses solely on technical aspects, and design organizations are reluctant to publicly share such information. The following are the main knowledge gaps we identified.

- *Who is financing?* This is the main question that should be asked to talk about the financial aspect of an LFR. No available document described a financial model. It is necessary to know if finances come from public or private investors, in which financial structure they are inserted (e.g., Mankala as in Finland, Exeltium as in France), as performed in EFWG (2018) for SMRs in the UK, whether they are accepting the risk of cost increases and time delays (very probable for FOAKs), and if they can cover the eventual extra costs. It is also necessary to study how finances are divided among debt, equity, and (for SMRs) self-financing.
- *Revenues.* Very few studies consider and compute revenues. We need to understand if they are reasonable and may represent an acceptable approximation for the selling of electricity and other products or services. The main example is NEA (2009), where the computed revenues for MYRRHA barely cover the estimated O&M costs. Moreover, NPPs, and therefore also LFRs, are very capital intensive, i.e., they have a large upfront cost that has to be recovered. For this type of plant, a secure (and stable) revenue stream is required. Hence, LFRs would probably need contracts like PPA (power purchase agreement) and CfD (contract for difference) but no document we considered introduces this topic. Moreover, LFRs may also be used for cogeneration, therefore, differentiating their output from the sole electricity. In this case, both thermal and electrical applications are possible, e.g., district heating, seawater desalination, biofuel production, hydrogen production, and other hard-to-abate processes (Locatelli et al., 2017).
- *Investors' involvement and risk.* Besides the public data already available, how is it possible to give reasonable, transparent, and credible cost estimations to attract investors? A risk analysis related to different investors and how they will affect the project in different situations is also required.

6. Conclusions

This work aimed at providing an overview of the knowledge and the state-of-the-art about economics and finance for LFRs, describing the results and gaps that were found. To do so, two SLRs, concerning both scientific and industrial literature, were performed. Regarding scientific literature, we found 12 articles strictly related to the objective of the research, 5 about Pb coolant, and 7 regarding LBE. Considering industrial literature, we added 12 documents, reaching a total of 24. Despite being one of the six "revolutionary" Gen-IV technologies, literature about LFR economics is limited and sometimes of low quality (it is not clear how the evaluations were performed and the assumptions that were made). Moreover, it is almost nonexistent for the financial part. Several knowledge gaps are present and are highlighted in Section 5. As can be seen in Table 13 and Table 14 the knowledge is fragmented among the documents and a global view is missing, since each of them gives only a small insight into the argument. Given the attention SMRs, and in particular LFRs, are gaining, a comprehensive economic and financial assessment for a specific design is still missing.

CRediT authorship contribution statement

Federico Tassone: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Marco Enrico Ricotti:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Stefano Lorenzi:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Giorgio Locatelli:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization.

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.

Data availability

No data was used for the research described in the article.

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References

AKME Engineering JSC, 2018. Construction of a Nuclear Power Plant with a Capacity of 100 MWT.

Alemberti, Alessandro, 2012. ELFR. The European fast reactor. Design, safety approach and safety characteristics. Technical Meeting on Impact of Fukushima Event on Current and Future Fast Reactor Designs. Germany. https://inis.iaea.org/collection/NCLCollectionStore/_Public/45/091/45091378.pdf.

Alemberti, Alessandro, 2021. Lead cooled fast reactors. Encyclopedia of Nuclear Energy. Elsevier, pp. 523–544. https://doi.org/10.1016/B978-0-12-819725-7.00001-5.

Alemberti, Alessandro, Caramello, Marco, Frignani, Michele, Grasso, Giacomo, Merli, Fabio, Morresi, Giulia, Tarantino, mariano, 2020. ALFRED reactor coolant system design. Nucl. Eng. Des. 370, 110884. https://www.sciencedirect.com/science/article/abs/pii/S0029549320303782?via%3Dihub.

ARIS, 2019. Status Report – SEALER-UK (Leadcold). https://aris.iaea.org/PDF/SEALER-UK_2020.pdf.

ARIS, 2020. Status Report – Westinghouse Lead Fast Reactor. Westinghouse Electric Company LLC)'. https://aris.iaea.org/PDF/W-LFR_2020.pdf.

ARIS, 2021. ARIS - technical data. https://aris.iaea.org/sites/overview.html.

Boccard, Nicolas, 2014. The cost of nuclear electricity: France after Fukushima. Energy Pol. 66, 450–461. https://www.sciencedirect.com/science/article/pii/S0301421513011440?casa_token=9p6UMIjcpHsAAAAA:RWRmy_b9tf1yb_iS9MoNDkNjOW7bzf2bKWQDCriLUQ99pXHYaRwGLdBGZTiop84vGZ-9Pb21.

Brigham, Eugene F., Ehrhardt, Michael C., 2008. Financial management: theory and practice. Twelfth ed. Thomson South-Western nibmehub.com/opac-service/pdf/read/Financial%20Management%20-Theory%20&%20Practice.pdf.

CambioEuro. 'Cambio Euro'. https://www.cambioeuro.it/.

Chikazawa, Yoshitaka, Konomura, Mamoru, Mizuno, Tomoyasu, Mito, Makoto, Tanji, Mikio, 2005. A conceptual design study of a small natural convection lead-bismuth–cooled reactor without refueling for 30 years. Nucl. Technol. 154 (2), 142–154. https://doi.org/10.13182/NT06-A372.

Cho, Jaehyun, Shin, Yong-Hoon, Hwang, Il Soon, 2015. Power maximization method for land-transportable fully passive lead–bismuth cooled small modular reactor systems. Nucl. Eng. Des. 289, 240–251. https://doi.org/10.1016/j.nucengdes.2015.04.027.

Choi, Sungyeol, Soon, Hwang Il, Hyun, Cho Jae, Bo, Shim Chun, 2012. URANUS: Korean lead-bismuth cooled small modular fast reactor activities. In: ASME 2011 Small Modular Reactors Symposium. In: https://asmedigitalcollection.asme.org/SMR/proceedings-abstract/SMR2011/54730/107/352348.

Cinotti, L., Briger, P., Grasso, G., 2018. Simplification, the Atout of LFR-AS-200', CN2vols. 45–140. IAEA. https://inis.iaea.org/collection/NCLCollectionStore/_Public/49/085/49085786.pdf?r=1.

Ciotti, Marco, Manzano, Jorge L., Grasso, Giacomo, Mansani, Luigi, Petrovich, Carlo, 2014. Lead Fast Reactor Sustainability. American Society of Mechanical Engineers Digital Collection. https://doi.org/10.1115/ICONE22-31092.

CORDIS, 2013. European Commission. Final Report Summary - LEADER (Lead-Cooled European Advanced Demonstration Reactor) | FP7. https://cordis.europa.eu/project/id/249668/reporting.

Davis, Cliff B., Kim, Dohyoung, Todreas, Neil E., Kazimi, Mujid S., 2002. Core power limits for a lead-bismuth natural circulation actinide burner reactor. Nucl. Eng. Des. 213 (2), 165–182. https://doi.org/10.1016/S0029-5493(02)00049-3.

Delene, Jerry G., Hudson II, C.R., 1993. Cost estimate guidelines for advanced nuclear power technologies. https://inis.iaea.org/collection/NCLCollectionStore/_Public/25/011/25011638.pdf?r=1.

Di Maddaloni, Francesco, Davis, Kate, 2017. The influence of local community stakeholders in megaprojects: rethinking their inclusiveness to improve project performance. Int. J. Proj. Manag. 35 (8), 1537–1556. https://doi.org/10.1016/j.ijproman.2017.08.011.

Du, Yadong, Wang, Leilei, Yu, Zhiyi, Zhang, Hanzhi, Li, Yanzhao, Yang, Ce, 2022. Multi-objective optimization of thermoeconomic and component size of supercritical carbon dioxide recompression cycle based on small-scale lead-cooled fast reactor. Int. J. Energy Res. 46 (10), 13570–13589. https://doi.org/10.1002/er.8076.

EFWG (Expert Finance Working Group), 2018. Market framework for financing small nuclear. https://assets.publishing.service.gov.uk/media/5b6962fc40f0b62e9d7fa8f1/DBEIS_11_-_Market_Framework_for_Financing_Small_Nuclear_EFWG_Final_Report_.pdf.

Ferroni, P., Stansbury, C., Liao, J., Utley, D., Levinsky, A., Wright, R., Gustavsson, E., Perry, H., Gorgemans, J., Lee, S.J., Ickes, M., Banyay, G., Franceschini, F., Harkness, A., Willis, J., Chrzanowski, J., Friedman, B., Tatli, E., Grasso, G., Tarantino, M., Frignani, M., 2019. The Westinghouse lead fast reactor program. 14th International Nuclear Fuel Cycle Conference. USA. https://pure.psu.edu/en/publications/the-westinghouse-lead-fast-reactor-program.

GIF - Generation IV International Forum website. https://www.gen-4.org/gif/.

GIF, 2014. Technology Roadmap Update for Generation IV Nuclear Energy Systems. https://www.gen-4.org/gif/upload/docs/application/pdf/2014-03/gif-tru2014.pdf.

GIF, 2023. GIF annual report 2022. https://www.gen-4.org/gif/jcms/c_216241/gif-annual-report-2022.

Grasso, Giacomo, Smith, Craig, Cinotti, Luciano, Artioli, Carlo, Corsini, Giovanni, 2010. Lead-cooled fast reactor (LFR) design: safety, neutronics, thermal hydraulics, structural mechanics, fuel, core, and plant design. In: Book: 'Handbook of Nuclear Engineering. Springer. https://link.springer.com/referenceworkentry/10.1007/978-0-387-98149-9_23.

Hejzlar, Pavel, Davis, Cliff B., 2004. Performance of the lead-alloy-cooled reactor concept balanced for actinide burning and electricity production. Nucl. Technol. 147 (3), 344–367. https://doi.org/10.13182/NT04-A3536.

Hejzlar, Pavel, Buongiorno, Jacopo, MacDonald, Philip E., Todreas, Neil E., 2004. Design strategy and constraints for medium-power lead-alloy–cooled actinide burners. Nucl. Technol. 147 (3), 321–343. https://www.tandfonline.com/doi/abs/10.13182/NT147-321.

IAEA - International Atomic Energy Agency website. https://www.iaea.org/.

IAEA, 2006. IAEA Safety Glossary, Version 2.0. http://www-ns.iaea.org/downloads/standards/glossary/glossary-english-version2point0-sept-06-12.pdf.

IAEA, 2007. Economic performance indicators for nuclear power plants. Tech. Rep. no. 437. Vienna https://www-pub.iaea.org/MTCD/Publications/PDF/TRS437_web.pdf.

IAEA, 2021. Benefits and challenges of small modular fast reactors. Tech. Rep. no. 1972. Vienna https://inis.iaea.org/collection/NCLCollectionStore/_Public/52/087/52087935.pdf?r=1.

IAEA, 2022. Advances in Small Modular Reactor Technology Developments. Vienna. https://aris.iaea.org/Publications/SMR_booklet_2022.pdf.

IAEA, 2023. Nuclear power reactor in the world. Ref. Data (2). Vienna. https://www-pub.iaea.org/MTCD/Publications/PDF/RDS-2-43_web.pdf.

Investopedia, 2022. What does finance mean? Its history, types, and importance explained. https://www.investopedia.com/terms/f/finance.asp.

Lee, Seungcheol, Shim, Hyung Jin, 2019. Design of Thorium-Fueled Subcritical Reactor Core for TRU Transmutation. Transaction of Korean Nuclear Society autumn meeting. https://www.kns.org/files/pre_paper/42/19A-406-%EC%9D%B4%EC%8A%B9%EC%B2%A0.pdf.

Li, Ming-Jia, Jie, Yan-Jun, Zhu, Han-Hui, Qi, Guo-Jia, Meng-Jie, Li, 2018. The thermodynamic and cost-benefit-analysis of miniaturized lead-cooled fast reactor with supercritical CO2 power cycle in the commercial market. Prog. Nucl. Energy 103, 135–150. https://doi.org/10.1016/j.pnucene.2017.11.015.

Li, Ming-Jia, Xu, Jin-Liang, Cao, Feng, Guo, Jia-Qi, Tong, Zi-Xiang, Zhu, Han-Hui, 2019. The investigation of thermo-economic performance and conceptual design for the miniaturized lead-cooled fast reactor composing supercritical CO2 power cycle. Energy 173, 174–195. https://doi.org/10.1016/j.energy.2019.01.135.

Lin, Jiming, Shi, Xiuan, Duan, Chengjie, Chen, Zhao, Cui, Dawei, Lei, Song, 2019. CLFR-300, an innovative lead-cooled fast reactor based on natural-driven safety technologies. IAEA Technical Meeting on Benefits and Challenges of Fast Reactors of the SMR Type. Italy. https://conferences.iaea.org/event/204/contributions/15877/attachments/8227/10866/07-IAEA_TM_Fast_SMRs_presentation_CLFR-300_Z.Chen.pdf.

Lloyd, Clara A., Roulstone, Tony, Lyons, Robbie E., 2021. Transport, constructability, and economic advantages of SMR modularization. Prog. Nucl. Energy 134, 103672. https://doi.org/10.1016/j.pnucene.2021.103672.

Locatelli, Giorgio, 2018. Why are megaprojects, including nuclear power plants, delivered overbudget and late? Reasons and remedies. arXiv. https://doi.org/10.48550/arXiv.1802.07312.

Locatelli, Giorgio, Bingham, Chris, Mancini, Mauro, 2014. Small modular reactors: a comprehensive overview of their economics and strategic aspects. Prog. Nucl. Energy 73, 75–85. https://doi.org/10.1016/j.pnucene.2014.01.010.

Locatelli, Giorgio, Fiordaliso, Andrea, Boarin, Sara, Ricotti, Marco E., 2017. Cogeneration: an option to facilitate load following in small modular reactors. Prog. Nucl. Energy 97, 153–161. https://doi.org/10.1016/j.pnucene.2016.12.012.

Lovering, Jessica R., Arthur, Yip, Nordhaus, Ted, 2016. Historical construction costs of global nuclear power reactors. Energy Pol. 91, 371–382. https://doi.org/10.1016/j.enpol.2016.01.011.

Mignacca, Benito, Locatelli, Giorgio, 2020a. Economics and finance of molten salt reactors. Prog. Nucl. Energy 129, 103503. https://doi.org/10.1016/j.pnucene.2020.103503.

Mignacca, Benito, Locatelli, Giorgio, 2020b. Economics and finance of small modular reactors: a systematic review and research agenda. Renew. Sustain. Energy Rev. 118, 109519 https://doi.org/10.1016/j.rser.2019.109519.

Mikityuk, Konstantin, Vasiliev, Alexander, Fomichenko, Peter, Schepetina, Tatyana D., Subbotin, Stanislav, Alekseev, Prokhor, 2002. RBEC-M lead-bismuth cooled fast reactor: optimization of conceptual decisions. In: International Conference on Nuclear Engineering, 2. https://doi.org/10.1115/ICONE10-22329.

NEA - Nuclear Energy Agency website. https://www.oecd-nea.org/jcms/j_6/home.

NEA, 2009. Independent evaluation of the MYRRHA project. https://www.oecd-nea.org/upload/docs/application/pdf/2019-12/nea6881-myrrha.pdf.

NEA, 2012. Nuclear energy data 2012/données sur l'énergie nucléaire 2012. https://www.oecd-nea.org/jcms/pl_14758/nuclear-energy-data-2012/donnees-sur-l-energie-nucleaire-2012?details=true.

NEA, 2023. The NEA Small Modular Reactor Dashboard. https://www.oecd-nea.org/jcms/pl_78743/the-nea-small-modular-reactor-dashboard?details=true.

NEWCLEO - newcleo Futurable Energy website. https://www.newcleo.com/.

Pittaway, Luke, Robertson, Maxine, Munir, Kamal M., Denyer, David, 2004. Networking and innovation: a systematic review of the evidence. Int. J. Manag. Rev. 5 (3–4), 137–168. https://www.researchgate.net/publication/227657266_Networking_and_Innovation_A_Systematic_Review_of_the_Evidence.

ROSATOM - Rosatom State Nuclear Energy Corporation website. https://www.rosatom.ru/en/index.html.

Sainati, Tristano, Brookes, Naomi, Locatelli, Giorgio, 2017. Special purpose entities in megaprojects: empty boxes or real companies? Proj. Manag. J. 48 (2), 55–73. https://journals.sagepub.com/doi/pdf/10.1177/875697281704800205?casa_token=R8JVuPzqfRcAAAAA:Mp6tNVxQZS-ePL6lt-VmVlHiYaRToUV6pb5TO_V7QGqtRbKSRIeuQLGSVEgnVMU5KSX-GRbVUpE.

SCK-CEN, 2018. About MYRRHA. Myrrha'. https://www.myrrha.be/about-myrrha.

Smith, Craig F., Halsey, William G., Brown, Neil W., Sienicki, James J., Moisseytsev, Anton, Wade, David C., 2008. SSTAR: the US lead-cooled fast reactor (LFR). J. Nucl. Mater. 376 (3), 255–259. https://www.sciencedirect.com/science/article/abs/pii/S0022311508000627.

Soto, Gabriel J., Lindley, Ben, Neises, Ty, Stansbury, Cory, Wagner, Michael J., 2022. Dispatch optimization, system design and cost benefit analysis of a nuclear reactor with molten salt thermal storage. Energies 15, 3599. https://www.mdpi.com/1996-1073/15/10/3599.

TASS, 2021. Cost of BREST Fast Reactor Construction Estimated at $1.3 Bln. Says Rosatom'. https://tass.com/economy/1300401.

USGS, 2017. Miner. Commod. Summ. https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/mineral-pubs/mcs/mcs2017.pdf.

USGS, 2023. Miner. Commod. Summ. https://pubs.usgs.gov/periodicals/mcs2023/mcs2023.pdf.

Wang, Xiang, Seidl, Marcus, Marcian-Juan, Rafael, 2015. Preliminary analysis of basic reactor physics of the dual fluid reactor concept. Proceeding of ICAPP, 15270. https://www.researchgate.net/profile/Xiang-Wang-55/publication/273384467_Preliminary_Analysis_of_Basic_Reactor_Physics_of_the_Dual_Fluid_Reactor_Concept/links/555cf0f408ae6f4dcc8bd1c5/Preliminary-Analysis-of-Basic-Reactor-Physics-of-the-Dual-Fluid-Reactor.

Wang, Ziguan, Luyu, Zhang, Yeon, Eing Yee, Linsen, Li, Feng, Shen, 2017. Pre-conceptual core design of a LBE-cooled fast reactor (BLESS). International Conference on

Mathematics and Computational Methods Applied to Nuclear Science and Engineering. Jeju, Korea. https://www.kns.org/files/int_paper/paper/MC2017_2017_2/P153S02-07WangZ.pdf.

Wider, Hartmut U., Carlsson, John, Loewen, Eric P., 2005. Renewed interest in lead cooled fast reactors. Prog. Nucl. Energy 47 (1), 44–52. https://doi.org/10.1016/j.pnucene.2005.05.003.

WNA - World Nuclear Association website. https://world-nuclear.org/.

WNA, 2020. Generation IV Nuclear Reactors. https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/generation-iv-nuclear-reactors.aspx.

WNA, 2021. Nuclear power in Russia. https://world-nuclear.org/information-library/country-profiles/countries-o-s/russia-nuclear-power.aspx.

WNA, 2022. Economics of Nuclear Power. https://world-nuclear.org/information-library/economic-aspects/economics-of-nuclear-power.aspx.

WNA, 2023. Asia's nuclear energy growth. https://world-nuclear.org/information-library/country-profiles/others/asias-nuclear-energy-growth.aspx.

Wu, Yican, Bai, Yungqing, Song, Yong, Huang, Qunying, Zhao, Zhumin, Hu, Liqin, 2016. Development strategy and conceptual design of China lead-based research reactor. Ann. Nucl. Energy 87, 511–516. https://www.sciencedirect.com/science/article/abs/pii/S0306454915004284?via%3Dihub.