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Uncertainties in estimating production costs of future nuclear technologies: A model-based analysis of small modular reactors

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A R T I C L E I N F O

Dataset link: https://github.com/weibezahn/smr-mcs

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A B S T R A C T

Predicting future costs of technologies not yet developed is a complex exercise that includes many uncertain parameters and functional forms. In that context, small modular reactor (SMR) concepts that are in a rather early development stage claim to have cost advantages through learning effects, standardized design, modularization, co-siting economies, and other factors, such as better time-to-market even though they exhibit negative economies of scale in their construction costs due to their lower power output compared to conventional nuclear reactors. In this paper, we compare two different approaches from production theory and show that they have a theoretically equal structure. In the second step, we apply these approaches to estimate a range of potential construction costs for 15 SMR projects for which sufficient data is available. These include water cooled, high temperature, and fast neutron spectrum reactors. We then apply the Monte Carlo method to benchmark the cost projections assumed by the manufacturers by varying the investment costs, the weighted average cost of capital, the capacity factor, and the wholesale electricity price in simulations of the net present value (NPV) and the levelized cost of electricity (LCOE). We also test whether the differences between the manufacturer estimates and ours differ between technology families of SMR concepts and apply a sensitivity analysis. Here we contribute to an intensifying debate in the literature on the economics and finance of SMR concepts. The Monte Carlo analysis suggests a broad range of NPVs and LCOEs: Surprisingly, the lowest LCOE is calculated for a helium-cooled high-temperature reactor, whereas all of the light water reactors feature higher LCOEs. None of the tested concepts is able to compete economically with existing renewable technologies, not even when taking their variability and necessary system integration costs into account. The numerical results also confirm the importance of the choice of production theory and parameters. We conclude that any technology foresight has to take as much of the case specifics into account, including technological and institutional specifics; this also holds for SMR concepts.

1. Introduction

Predicting future costs of technologies not yet developed is a complex exercise that includes many uncertain parameters and functional forms. Production theory provides some heuristic concepts such as "economies of scale" and "learning effects", but the application of these concepts is not straightforward. Neither can "laws" observed from past data be easily extended to forecast cost trends of technologies under development. Hence, while learning effects have driven down the costs of most production processes thus far [1–3], nuclear power plants have been characterized by rising average capital costs as units became larger and production increased [4–9]. Therefore, any technology foresight has to take as much of the case specifics into account, including technological and institutional specifics.

Recent developments of so-called advanced nuclear reactor concepts with low power ratings are a particularly interesting case of applied production theory and cost forecasting. The development of these SMR concepts (sometimes called "small modular reactors" in the literature) has in part been driven by an increasing frustration with the high and ever-mounting costs and long construction times of nuclear power plants with high power capacities (∼1000 MW_{el} and even up

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to 1660 MW_{el}). Also, formerly dominating nuclear powers, such as the US, the UK, and France have lost their national champions in reactor technology over the last decades and may be interested in reversing this trend. Given that nuclear power still has rising costs whereas other energies are becoming cheaper [10,11], and that Russian and Chinese equipment producers are now dominating global export markets [12–14], a technological revolution is called for to overcome this double challenge, proposing to develop SMR concepts by respectively domestic producers [15,16].

In this paper, we compare different approaches to forecast construction cost estimates for SMR concepts that are in a rather early development stage. We define SMR concepts as nuclear power plants, in which a single reactor has an electrical power output of less than or equal to 300 MW_{el} (or a thermal power output of less than 1000 MW_{th}), and which can be based on water-cooled, or other (non-water cooled) reactor designs [17,18]. SMR concepts are now being developed, to different degrees, in the countries with major nuclear development programs (USA, UK, France, Russia, China) and some others (e.g., Canada, South Korea, Japan, India, South Africa, Sweden), and a few potential nuclear entrant countries (e.g., Saudi-Arabia and Jordan but also Denmark) [19]. Very optimistic proponents of SMR concepts even see an important future role for these technologies in combatting climate change [16], though this seems somewhat premature given the high levels of uncertainty still prevailing. We explore different strands of literature in estimating construction cost trends for SMR concepts based on production theory and derive construction cost ranges for specific SMR concepts currently explored. These production theory-based forecasts are then compared with current estimates advertised by the manufacturers of SMR concepts themselves. A similar comparison between estimated forecasts and manufacturer data is carried out for the net present value (NPV) and the levelized costs of electricity (LCOE), a common measure to compare different generation technologies. The approach in this paper is positive, that is, we do not include judgment values about the normative assessment of SMR concepts (see the summary of Pistner et al. [20, pp. 24–30] for additional socio-technical aspects).

The paper contributes to the literature in two aspects:

- We provide concrete numerical analysis to compare results from different production theories on learning effects. Concretely, we compare the approach used by Roulstone et al. [16] with the more complex approach suggested by Rothwell [21] that uses a more flexible form. We show that the structure of both models is identical when setting the right scaling factor and that the choice of the model has significant effects on the results: Notably, the latter approach could—depending on the chosen scaling factor—imply a cost estimation below the technologically identical reference reactor, allowing for much lower cost prediction parameter ranges.
- We assess the production costs of SMR concepts as advertised by manufacturers that we benchmark with theory-based estimates. Naturally, manufacturers tend to be optimistic with respect to their future competitiveness, and thus a comparative benchmark analysis is useful to put these into perspective. In passing, we also test whether the differences between the manufacturer estimates and ours differ between technology families of SMR concepts (i.e., light water, high temperature, or fast neutron spectrum reactors). Here we contribute to an intensifying debate in the literature on economics and finance of SMR concepts [22–25].

The remainder of this paper is structured in the following way: The next Section 2 introduces our unique data set on SMR concepts, assembled from both manufacturer announcements and other publicly available sources like trade press, and discusses the range of parameters, mainly the scaling effect and the learning effect. We also introduce a technology-based differentiation of SMR concepts. In Section 3 we explain the underlying theory of production and apply it to nuclear power plants; we also introduce the distinction between two theoretical approaches and the effects of different parameter choices on construction cost estimates. The data and parameters are then fed into a Monte Carlo simulation to provide likely ranges for future production costs. Results and variance-based sensitivity analyses are presented and discussed in Section 4 and Section 5 concludes and provides an outlook.

2. SMR concepts, data, and parameters

2.1. Motivation and structure of SMR concepts

The nuclear industry is characterized by particularly complex upstream, investment and production, and downstream activities. It has been described as a highly complex system good [26]. Upstream, mining and fuel processing and production need to be coordinated with the specific use of the fuel, and its technical, physical, and chemical specifications. Producing and operating a nuclear reactor itself is very complex, due to the high reactivity of the process, the radioactivity involved, and the enormous amounts of heat constantly produced. In addition to the spent fuel, several activation and fission products have to be considered. Downstream, the decommissioning and dismantling of the process are challenges that have been ignored for a long time, requiring specific knowledge, long-term planning, and—ideally—appropriate design right from the beginning. Last but not least, intermediate and long-term storage of nuclear waste is a technical and financial challenge that any SMR will have to cope with and plan for, too.

Between the 1950s, when the first commercially used nuclear power plant went online, and today, the power ratings of reactors have continuously increased. The first reactors in the Soviet Union (Obinsk, 1954), the UK (Calder Hall, 1956), and the US (GE Vallecitos, 1957; Shippingport, 1957; Dresden-1, 1960) were in the two- to three-digit MW range [14]. The water-cooled reactors then diffused globally and increased their power ratings per unit at the beginning of the 1970s. The largest number of reactors (over 100) were built in the USA but with little standardization and, thus, unable to reap economics of production [4,27]. The most relevant number of reactors of similar design was built in France, but even there no significant learning effects could be identified—or they were even negative [5–7]. Today, the largest units reach 1600 MW_{el}, about 280 times the amount of the first commercial reactors.[1] However, as is extensively documented in the literature, none of these light water reactors has been able to compete with other generation technologies, be it coal, natural gas, and nowadays in some cases renewables [8,10,28–30]. In addition, over the last decades, the major reactor companies have either gone bankrupt or converted their business structure through spin-offs of their nuclear division or were sold; examples are Westinghouse[2] and General Electric[3] in the US, Babcock & Wilcox[4] in the UK, and Areva[5] in France.

The development of SMR concepts can be interpreted as an attempt to overcome recently identified industrial-wide challenges, that is, economic competitiveness and the re-establishment of national technological leadership.[6] Although SMRs are designed for low power

[1] Based on the assumption that Obinsk is the first nuclear power plant with 6 MW_{el} as gross capacity. At the beginning of 2022 the IAEA Power Reactor Information System lists the Chinese PWR Taizhou-2 unit with a reference capacity of 1660 MW_{el} and a net capacity of 1750 MW_{el}.

[2] Sabino and Abatemarco [31] describe victimization by cost overruns at four nuclear plants has forced Westinghouse to file for chapter 11.

[3] For more information see [32].

[4] For more details on the spin-off of the nuclear division of Babcock and Wilcox please see [33].

[5] For more information see [34, p. 688] or https://www.world-nuclear-news.org/C-New-Areva-changes-name-to-Orano-2301185.html.

[6] Then U.S. Secretary of Energy Steven Chu summarized the mission very bluntly: “America is on the cusp of reviving its nuclear power industry.” [15].

output (the IAEA definition puts it below 300 MW_{el}), they will "have compact designs and could be made in factories and transported to sites by truck or rail. SMRs would be ready to "plug and play" upon arrival." [15, p. 2]. In addition to large-scale production, other factors are also relevant, such as co-siting economies, modularization, and low construction times [23]. A description of concrete SMR concepts and respective technical and economic data is provided in the next section.

2.2. Selected SMR concepts addressed in this paper

The idea of nuclear reactors with relatively low power ratings goes back to the early days of the 1950s, and almost all use cases discussed today had already been considered at the time, in particular the co-generation of electricity and heat, the use in remote areas, and water desalination [24,25]. Historically, the first nuclear reactors with low power ratings were developed for naval propulsion, both in the US (Westinghouse's S2 W, the first naval ship "Nautilus" in 1954), and the Soviet Union ("Lenin", 1955). Today, the Russian KLT-40S reactors (the first one installed on the "Akademik Lomonosov" in 2020) are based on earlier reactor designs for ice breakers [19, p. 111], [20, p. 33]. Other early reactors with low power rating are Elk River (first criticality in 1962, 22 MW_{el}), a boiling water reactor (BWR), and non-water-cooled reactors, such as the high-temperature reactor (HTR) Peach Bottom (1966), and the molten salt reactor experiment MSRE (1960).

The renaissance of SMR-enthusiasm goes back to U.S. Secretary of Energy at the time Stephen Chu identifying SMRs as "America's new nuclear option" [15, p. 1]. Since then, the term "SMR" that had been used for decades to designate "small-and-medium-sized reactors" [35, 36] was re-branded as "small modular reactors". Over the last decade, a vast literature has emerged on SMR concepts, thus leading to a quite heterogeneous grouping of what the universe of SMRs is composed of. In most general terms, there is a broad consensus that SMRs are nuclear reactors for low power output, that is, below 300 MW_{el} (though some exceptions exist, such as Rolls-Royce's UK SMR with 440 MW_{el}) with some degree of modularity in piece production and/or final assembly.

The International Atomic Energy Agency (IAEA) currently lists 48 SMR concepts in their advanced reactor information system (ARIS)[7] database, whereas the current supplementary report lists 83 concepts from 18 different countries involved in the development of those concepts [37]. Besides this, the World Nuclear Association (WNA) publishes a list, which differs by the stages of development of SMR concepts. It is divided into "(…) operating", "(…) under construction", "(…) near term development – development well advanced", "(…) designs at earlier stages (or shelved)", "very small reactor designs being developed (up to 25 MW_{el})", and includes technical information as well as a brief history. As of May 2023, the WNA website lists 58 SMR concepts.[8] Pistner et al. [20] (in German, with English summary) contains an extensive list of 136 reactor types and SMR concepts of which 31 are described in more detail (such as the CEFR, HTR-10, and HTTR).

The SMR segment is very dynamic and includes a lot of anticipation and technical and economic uncertainty. Obtaining data on future investment and/or operation costs, technical advances, and timelines is difficult. In addition, due to different underlying assumptions, most of this data cannot easily be compared with each other. Therefore, all numerical results on SMRs should be seen with caution. To the best of our knowledge, this paper contains the broadest range of SMR data assembled thus far, based on public information, and transparently documented in Appendix A. Based on data availability, this paper covers 19 SMR concepts of different reactor technologies: water-cooled SMRs, both for fixed installations and marine-based, other (non-water-cooled) SMR concepts such as high-temperature gas-cooled concepts, fast neutron spectrum, molten salt reactor concepts, lead-cooled reactor concepts, and micro reactor concepts. Since 2018 the IAEA lists very-low-capacity reactors in a special category, named this category in 2020 for the first time "micro-sized small modular reactors" [19], and has added a new category of reactors with power ratings below 10 MW_{el}, called "micro-reactors" (sometimes also called "nuclear batteries"), of which we include one (e-Vinci).

2.3. Data

Our unique data set in this paper consists of 19 SMR concepts through updates to the data set of Pistner et al. [20] with additional information from various international sources. Since we are looking at concepts currently under development we also have to rely on non-academic resources like information available directly from manufacturer reports or from secondary sources like industry-specific specialized press outlets. This information is all based on manufacturer statements and cannot be independently verified. Table 1 shows the SMR concepts covered in this paper together with their associated overnight construction costs (OCCs) as advertised by the manufacturer, their capacities, and their proposed design lifetime. Furthermore, Appendix A consists of brief concept descriptions and Appendix B of further model assumptions and their associated sources.

For our analysis, we need additional data such as fuel costs and operation and maintenance (O&M) costs for the considered SMR concepts. For concepts where we were not able to retrieve specific data, we estimated those costs as averages of available current cost factors within the same reactor technology group of SMR concepts or used global averages. In most cases, we were able to retrieve the needed data from academic sources. Only two concepts rely on trade press information from manufacturers for their operations and maintenance costs. We normalized all costs in this paper to USD_{2020}.

3. Methodology: Production models applied to SMR concepts

Due to their lower power output, SMR concepts exhibit negative economies of scale compared to conventional reactors with higher power output with regard to their overnight construction costs. To make up for this disadvantage, SMR concepts are advertised to realize cost advantages through learning curve effects, standardized design, modularization, co-siting economies, and other factors, such as better time-to-market [38,39]. Lokhov et al. [40] describe the serial production of SMR concepts as a key element for their competitiveness. Mignacca and Locatelli [23] see that the advantage of SMR concepts is determined through their modularization and modularity. Also, Lloyd Peterhouse [41] describes the degree of modularization as a cost-decreasing factor influencing the construction time. Operating and maintenance as well as fuel costs could theoretically also make up for some of the cost disadvantages. In the following, we will describe two common approaches to estimating construction costs and influencing factors and will show that the underlying basic structure is the same.

3.1. Two approaches to estimate production costs with respect to influencing cost-decreasing effects

The literature provides a variety of theoretical approaches to estimate production costs and corresponding influencing effects for technologies under development. In this paper, we start with an introduction to a commonly used, general approach to estimating the construction costs of reactor technologies. In a second step, we expand this theory with the description of two common approaches from the literature and their basic production economic effects and show their differences. The main difference between the two is the treatment of the scaling factor.

[7] https://aris.iaea.org/sites/SMR.html

[8] https://www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/small-nuclear-power-reactors.aspx

Table 1
SMR concepts considered in this paper and their key characteristics as communicated by manufacturers.

Project	Type	Construction Cost [USD_{2020}/MW_{el}]	Capacity [MW_{el}]	Lifetime [years]
BWRX-300	BWR	2,250,000	300	60
UK-SMR[a]	PWR	5,215,937	443	60
SMR-160	PWR	6,312,500	160	80
SMART	PWR	10,186,916	107	60
NuScale	PWR	3,466,000	77	60
RITM 200M	PWR	4,212,000	53	60
ACPR 50S	PWR	8,532,000	40	40
KLT-40S	PWR	13,531,429	35	40
CAREM	PWR	23,187,500	30	40
EM2	HTR/GFR	4,373,300	265	60
HTR-PM	HTR	5,400,000	210	40
PBMR-400	HTGR	1,550,000	165	40
ARC-100	SFR	5,050,000	100	60
CEFR	SFR	23,034,536	20	30
4S	SFR	2,500,000	10	60
IMSR (300)	MSR	4,054,266	195	56–60
SSR-W	MSFR	1,950,000	30	60
e-Vinci	MR	5,771,429	3.5	40
Brest-OD-300	LFR	4,160,000	300	30

[a] We also include this reactor concept since it is close to 300 MW_{el} and below 500 MW_{el}.

In general, Black et al. [42] describe the simplified relationship of total construction costs c of nuclear power plants with differing capacities p with a sub-index smr corresponding to SMR concepts with low capacity and a sub-index lr corresponding to known high capacity nuclear power plants through:

$$\frac{c_{\text{smr}}}{c_{\text{lr}}} = \frac{p_{\text{smr}}}{p_{\text{lr}}}. \tag{1}$$

However, since basic production economic effects as described in Section 2 apply, we now introduce two approaches for production cost estimation from the literature taking these into account. Roulstone et al. [16] propose a simple model with c for costs, a constant scaling parameter β, a learning rate x, a factor $d(n) = \log(n)/\log(2)$ that takes into account the doubling in production with $n \in \mathbb{N}$ being the number of units produced and p for the plant's power output[9]:

$$c_{\text{smr}} = c_{\text{lr}} \cdot \left(\frac{p_{\text{smr}}}{p_{\text{lr}}}\right)^{\beta} \quad \text{and} \quad c_{\text{smr},n} = c_{\text{lr}} \cdot \left(\frac{p_{\text{smr}}}{p_{\text{lr}}}\right)^{\beta} \cdot (1-x)^{d(n)}. \tag{2}$$

In his standard textbook on the economics of nuclear power, Rothwell [21, p. 113,Eq. 3.5.2] suggests attaching specific, size-dependent weights to the scaling parameter γ (all other variable definitions as in Eq. (2)):

$$c_{\text{smr}} = c_{\text{lr}} \cdot \left(\frac{p_{\text{smr}}}{p_{\text{lr}}}\right) \cdot \gamma^{\frac{\ln p_{\text{smr}} - \ln p_{\text{lr}}}{\ln 2}} \quad \text{and}$$
$$c_{\text{smr},n} = c_{\text{lr}} \cdot \left(\frac{p_{\text{smr}}}{p_{\text{lr}}}\right) \cdot \gamma^{\frac{\ln p_{\text{smr}} - \ln p_{\text{lr}}}{\ln 2}} \cdot (1-x)^{d(n)}. \tag{3}$$

It can be noticed that the assumption for learning rates seems to be a hypothetical one defined by only seven operational SMR concepts in 2021 (CEFR, CNP-300, EGP-6, HTR-10, HTTR, the KLT-40S "Akademik Lomonosov", PHWR-220) with costs above first budget expectations [20, pp. 72, 174] and no specific supply chain or factory production in place. The current choice of scaling factors in our understanding has first been derived through the statistical work by Woite [43] in 1978 for conventional nuclear power plants with high capacities. Their validity for the cost estimation of nuclear power plants with low capacities, therefore, seems to be quite uncertain, since the main arguments for cost reductions are the envisioned factory production applying new methods and processes [37].

To summarize, the current cost estimation approach is directly dependent on the right choice of the scaling factor, the learning rate, and the factor for doubling in production numbers. Scaling parameters, commonly described in the industry-specific literature, range typically between 0.20 and 0.75 as discussed in a joint study from the NEA [44, p. 37] from the year 2000, which cites the statistical study of Woite [43] aside from the unspecific "0.6 economies of scale rule" [45]. For learning rates, in contrast to the high rates of the photovoltaic but also the wind industry in the last years [11,46,47], the summarizing study of Mignacca and Locatelli [23] cites Lewis et al. [48] for SMRs with a range between 5% and 10% for every doubling in production.

As a first step, by applying Eqs. (2) and (3) we obtain estimates of construction costs for various different SMR designs based on reported SMR capacities, and compare the results with the currently available construction costs advertised by manufacturers (Fig. 1). Here, we use a best-case literature-based learning rate of $x = 10\%$, one doubling in production, that is, $n = 2$, and a scaling parameter in the range of $[0.20; 0.75]$ assumed to be the same for Eqs. (2) and (3).

As a first result, notice that the predicted construction costs intervals, c_{smr}, obtained by either Eq. (2) (blue) or (3) (green) for scaling parameters in $[0.2; 0.75]$ are significantly larger compared to currently advertised manufacturer costs (red). The only exception is given by the SMR design CAREM whose advertised manufacturer costs are contained in the cost interval with respect to Eq. (2). In general, it can be discovered that the distance between the minimal computed construction costs using Eq. (2) and the advertised manufacturer construction costs is smaller than the corresponding distance resulting from Eq. (3). Moreover, observe that, by using the same scaling parameters, the computed cost intervals based on Eq. (2) are significantly smaller than the ones obtained from Eq. (3).

Next, we examine the structure of Eqs. (2) and (3) and show that both equations are structurally the same when setting the right scaling

[9] As an illustration, consider two exemplary reactor designs from Westinghouse, an American company. The first design is a PWR SMR with a capacity of $p_{\text{smr}} = 225\,MW_{el}$, while the second design is a large PWR known as the AP1000 with a capacity of around $p_{\text{lr}} = 1100\,MW_{el}$. The cost per kW_{el} of constructing an AP1000 in this example is estimated to be 6000 USD/kW_{el}, that is, $c_{\text{lr}} = 6000\,USD/kW_{el} \cdot p_{\text{lr}}$. However, if the reactor design of the AP1000 is replaced by an SMR design higher costs per kW_{el} are expected. For instance, applying Eq. (2) with a scaling factor of $\beta = 0.55$ results in a cost estimate of 12,250 USD/kW_{el}. If, additionally, learning effects are assumed to reduce the costs by a factor $x = 0.06$ whenever the number of produced SMRs is doubled, more than $n = 3000$ ($d(n) = 11.55$) SMRs have to be produced until the cost per kW_{el} of an AP1000 is reached [20].

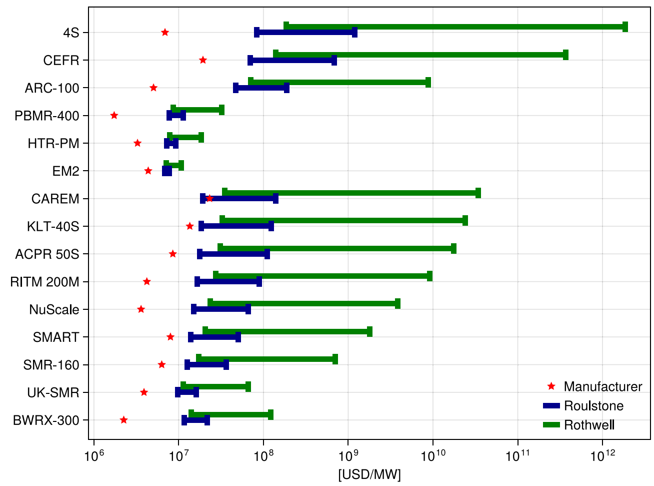


Fig. 1. Manufacturer advertised costs vs. theoretically estimated costs.

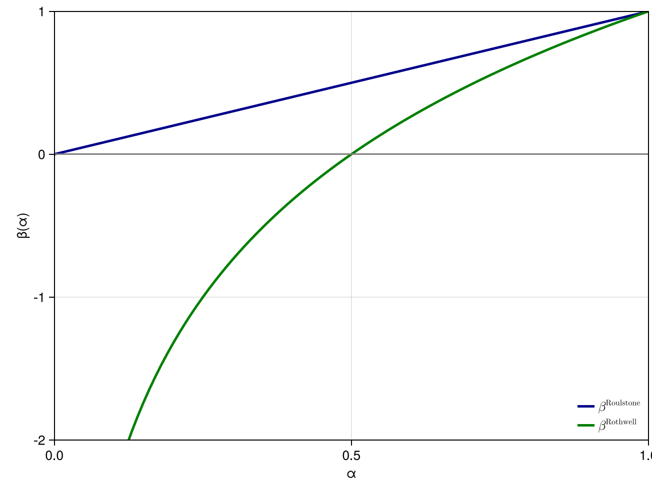


Fig. 2. Comparison of the scaling functions $\alpha \mapsto \beta^{\mathrm{Roulstone}}(\alpha) = \alpha$ and $\alpha \mapsto \beta^{\mathrm{Rothwell}}(\alpha) = 1 + (\ln \alpha)/(\ln 2)$ as a function of $\alpha \in [0,1]$.

factors, that is, there is a function $\alpha \mapsto \beta^{\mathrm{Rothwell}}(\alpha)$ such that, for a given value of γ, the costs, c_{smr}, derived by means of Eq. (2) with $\beta = \beta^{\mathrm{Rothwell}}(\gamma)$ and Eq. (3) with γ coincide. Clearly, an elementary computation reveals that the scaling factor in Eq. (3) can be transformed into:

$$\gamma^{\frac{\ln p_{\mathrm{smr}} - \ln p_{\mathrm{lr}}}{\ln 2}} = \mathrm{e}^{\frac{\ln \gamma}{\ln 2} \cdot \ln \frac{p_{\mathrm{smr}}}{p_{\mathrm{lr}}}} = \left(\frac{p_{\mathrm{smr}}}{p_{\mathrm{lr}}}\right)^{\frac{\ln \gamma}{\ln 2}}. \tag{4}$$

With that, Eq. (3) can be written as:

$$c_{\mathrm{smr}} = c_{\mathrm{lr}} \cdot \left(\frac{p_{\mathrm{smr}}}{p_{\mathrm{lr}}}\right)^{1+\frac{\ln \gamma}{\ln 2}} \cdot (1-x)^{d(n)}. \tag{5}$$

Thus, Eqs. (2) and (3) are equivalent if we set:

$$\beta = 1 + \frac{\ln \gamma}{\ln 2} \qquad \Longleftrightarrow \qquad \gamma = 2^{\beta - 1}. \tag{6}$$

In particular, this shows that the desired function, $\beta^{\mathrm{Rothwell}}$, is given by $\beta^{\mathrm{Rothwell}}(\alpha) = 1 + (\ln \alpha)/(\ln 2)$. For the sake of convenience, we also define the function, $\alpha \mapsto \beta^{\mathrm{Roulstone}}(\alpha) = \alpha$ (see Fig. 2 for the qualitative behavior of the graph of $\beta^{\mathrm{Roulstone}}$ and $\beta^{\mathrm{Rothwell}}$). Obviously, for the choice $\beta = \gamma = 1$, Eqs. (2) and (3) coincide with the naive scaling relation as given in Eq. (1). However, for $\beta = 0$ (corresponding to $\gamma = 0.5$ by Eq. (6)) the construction costs, c_{smr}, derived from Eq. (2) coincide with the cost c_{lr}, whereas in the limit when γ tends to 0 the construction costs obtained from Eq. (3) diverge. In particular, for sufficiently small values of $\gamma > 0$ the construction costs, c_{smr}, may even become larger than the cost of the reference reactor, c_{lr}, which would render the investment fully uneconomical compared to the reference reactor. This effect can also be observed in Fig. 1, where the upper values for the depicted range of Eq. (3) (green) reach several orders of magnitude higher than those of Eq. (2).

For this reason, we assume that the chosen scaling parameter should, in our view, not be interpreted as γ in Eq. (3) but rather as β in Eq. (6) and the values of γ should then be derived thereof, using Eq. (6).[10] In doing so, the limits of construction costs in Fig. 2 would coincide for both theories. Yet, when sampling the scaling parameter β, say, uniformly on an interval, e.g. $[0.2; 0.75]$, and γ uniformly on the effective interval obtained from Eq. (6), the distribution of the constructions costs, c_{smr}, differs depending on reactor size and the reference reactor. Fig. 3 shows a normalized histogram for each of the SMR designs investigated in this paper both using Eq. (2) (blue) and Eq. (3) (green). Therefore, in the following analysis, we are only using the production cost estimation theory of Roulstone et al. [16].

3.2. Two common measurements to promote a possible investment

In energy economics, two measurements evaluating investments into a possible generation technology are common: the net present value (NPV) and the levelized costs of electricity (LCOE).

The NPV, a measurement of the profitability of investments is defined through:

$$NPV = \sum_{t=0}^{T} \frac{e_t}{(1+r_t)^t} \tag{7}$$

with e_t describing the net cash flow and r_t the interest rate in a given time period $t \in (0,\dots,T)$, respectively [49], therefore discounting future cashflows to their present value. In the case of SMR concepts (and all generation technologies for that matter), cash flows depend on construction costs as overnight construction costs (OCC) in the construction phase as well as expenditures for labor and maintenance (fixed and variable O&M costs) and fuel and pollution costs during the operating phase for negative flows and on energy prices and demand (load factor) for positive flows. Some of those values may change over time. To simulate cash flows, we divide the total time horizon into two parts, the construction period $(1,\dots,T_{\mathrm{con}})$ and the operation period $(T_{\mathrm{con}+1},\dots,T_{\mathrm{con}} + T_{\mathrm{op}})$, and we define the total time horizon, T, by $T = T_{\mathrm{con}} + T_{\mathrm{op}}$.

We assume that the OCC is spent in equal parts during the construction period. This results in a time-dependent OCC_t defined as the ratio of overnight construction costs and construction time within the construction period that vanishes afterward. For each time t the corresponding interest rate r_t is considered as the weighted average cost of capital (WACC) defined as the average of the cost of interest on debts from bondholders and banks and the cost of equity capital from investors [21]. Hereby, also the interest during construction (idc) is implicitly included.

In order to calculate the long-run average cost of electricity we follow the well-establish methodology by Short et al. [50, pp. 47–51] and first define the total life-cycle cost ($TLCC$) through:

$$TLCC = \sum_{t=0}^{T} \frac{c_t}{(1+r_t)^t} \tag{8}$$

[10] For instance, the considered interval $[0.2; 0.75]$ for the scaling parameter β transforms into the interval $[0.57; 0.84]$ for the scaling parameter γ via Eq. (6).

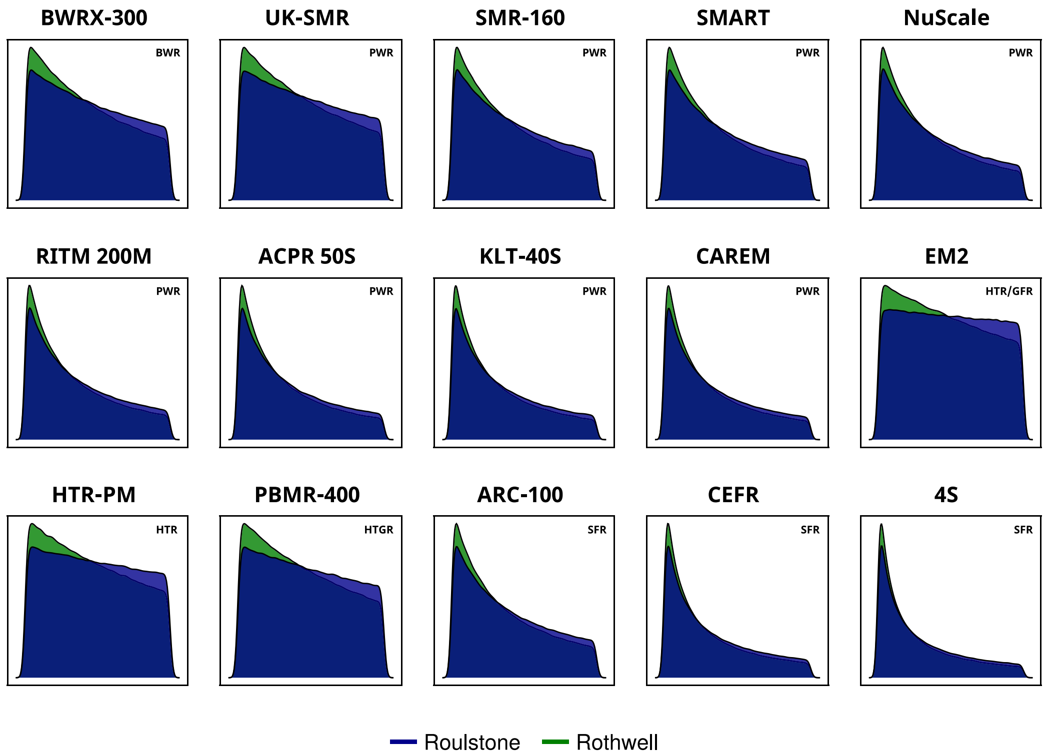


Fig. 3. Comparison of probability density functions for theoretically estimated investment costs. The horizontal axis represents investment costs while the vertical axis represents the normalized probability.

with T denoting the total lifetime of the project and c_t being the full costs in year t. This equation reflects the net present value of the costs (i.e., negative cash flows) accrued by the investment as described for Eq. (7) but without taking positive cash flows into account.

We can then define the levelized costs of electricity as a comparative measure of the net present costs of electricity generation per unit of energy for an examined project through:

$$LCOE = \frac{TLCC}{\sum_{t=0}^{T}\left(q_t \cdot (1+r_t)^{-t}\right)} \tag{9}$$

with q_t being the quantity of electricity produced in year t (depending on the load factor and demand).

3.3. Simulation of uncertainties with the Monte Carlo method

Since uncertainties exist in the input parameters—for example, interest rate, investment cost, load factor, and electricity price—for both the NPV and LCOE computation we rely on Monte Carlo experiments, that is, a computational algorithm based on the repeated random sampling of uncertain input qualities to obtain numerical results on the likelihood of a certain output parameter. Monte Carlo methods are commonly successfully used for simulation, estimation, inference, and learning in science and engineering, cf. the textbook of Barbu and Zhu [51] for an in-depth discussion of different variants of Monte Carlo algorithms and convergence results. In the context of electricity systems, this technique has been also well accepted [52–55].

Since we collected a unique data set of manufacturer advertised construction and operation costs (Section 2) and identified two common theoretical approaches (Eqs. (2) and (3)) for construction cost estimation with a similar structure (Section 3), we are now able to define two scenarios, one for the more "theoretical" cost estimation approach and one for the manufacturer advertised costs to compute NPV and LCOE and simulate uncertainties with the help of the Monte Carlo method. In the theoretical scenario, we sample over the scaling parameters and thus place more emphasis on the cheaper investment costs, and in the scenario with the given manufacturer costs we limit ourselves to the uncertainty in the capital costs, the wholesale electricity price, and the load factor. Naturally, also the manufacturer advertised costs inhibit uncertainty since the product does not yet exist commercially on the market. Since we have no information on the possible distribution of those costs we have decided to treat the manufacturer information as deterministic. The results are still comparable when considering mean or median values, although the variance in the results is naturally higher for the case of theoretically estimated cost parameters due to the additional uncertain parameter. Considering we decided to test the best case, we used the best case assumption for learning rates from the literature at 10% and ignored the uncertain costs of decommissioning and the costs of licensing.

For the uncertainty in the capital cost parameter, we followed Rothwell [21, p. 77] and defined the WACC in a range of [0.04; 0.10] and used the average of the non–consumer electricity price from Eurostat between 2007 and 2020 to define the wholesale electricity price through a range of [52.2; 95.8] USD_{2020}. For the load factor, we followed Rothwell [21] and assumed a range between [0.75; 0.85]. Some manufacturers assume (unproven) higher load factors even above 95%, yet in electricity systems based on high shares of intermittent renewables, nuclear has to become more load- and supply-following, thereby offering flexibility to the system. This accommodating behavior negatively impacts the expected realizable load factor. All assumptions for uncertain parameters with their expected distribution are displayed in Table 2.

Further assumptions for operation and maintenance (O&M) costs and fuel costs with sources can be reviewed in Appendix B. Since the time of construction is a critical issue of success through various cost overruns, we assumed a best case of three years for all reactor concepts.

Table 2
Parameters used in the Monte Carlo simulation.

Parameter	Range	Distribution	Source
Number of simulation runs N	1e6	–	–
Learning rate	0.10	–	[23]
Scaling parameter	[0.20; 0.75]	Uniform	[44]
Average wholesale electricity price for industrial consumption between 2007 and 2020 (USD_{2020}/MWh)	[52.2; 95.8]	Uniform	[56]
Weighted average cost of capital	[0.04; 0.10]	Uniform	[21]
Load factor	[0.75; 0.85]	Uniform	[55]

3.4. Variance-based sensitivity analysis

Since under the Monte Carlo method, multiple factors are assumed to be uncertain and drawn as random variables from various different distributions they can potentially all influence the variance of the calculated NPV and LCOE, respectively. In order to analyze the relative influence of a specific input random variable on the variance of the model output we performed a sensitivity analysis following the methodology of Saltelli et al. [57].

In general, given a vector $X = (X_1, \dots, X_k)$ of independent, real-valued random variables, we set $Y = f(X_1, \dots, X_k)$ for some function $f : \mathbb{R}^k \to \mathbb{R}$ such that the random variable Y has a finite second moment, that is, $\mathbb{E}_X[Y^2] < \infty$, where we denote by $\mathbb{E}_X$ the expectation with respect to the distribution of the random vector X. Likewise, we write $\mathbb{V}_X$ to denote the variance with respect to the distribution of X. In the later application, the function, f, will be either the NPV or the LCOE, respectively, whereas the random vector, X, consists of our four random input variables, namely, the random scaling parameter, the random wholesale electricity price, the WACC and the random load factor. Further, to simplify notations, we write $X_{\sim i}$ to denote the random variable that is obtained from the random variable X by deleting the i-th component, e.g. $X_{\sim i} = (X_1, \dots, X_{i-1}, X_{i+1}, \dots, X_k)$. Then, the so-called variance-based first-order effect, S_i, of the random variable X_i is defined as:

$$S_i = \frac{\mathbb{V}_{X_i}\left[\mathbb{E}_{X_{\sim i}}[Y \mid X_i]\right]}{\mathbb{V}_X[Y]}. \tag{10}$$

The first-order effect, S_i, measures the fraction of the total variance $\mathbb{V}_X[Y]$ of a model output, Y, that can be explained by the variance of the conditional model output when the input factor X_i is kept fixed. Notice that, in general, the first-order effects $S_1, \dots, S_k$ sum up to a number less than or equal to one, whereas equality is obtained if also all higher-order effects are taken into account. Analogously, the total-effect, S_i^{total}, is defined as:

$$S_i^{\text{total}} = \frac{\mathbb{E}_{X_{\sim i}}\left[\mathbb{V}_{X_i}[Y \mid X_{\sim i}]\right]}{\mathbb{V}_X[Y]} = 1 - \frac{\mathbb{V}_{X_{\sim i}}\left[\mathbb{E}_{X_i}[Y \mid X_{\sim i}]\right]}{\mathbb{V}_X[Y]}. \tag{11}$$

In this case, all factors except for X_i are kept fixed. In order to compute both the (conditional) expectation and variance that appear in Eqs. (10) and (11), we rely on empirical averages. More precisely, in this paper, following the theory of Saltelli et al. [57], we approximate S_i by:

$$\mathbb{V}_{X_i}\left[\mathbb{E}_{X_{\sim i}}[Y \mid X_i]\right] \approx \frac{1}{N}\sum_{j=1}^{N} f(B)_j \left(f(A_B^{(i)})_j - f(A)_j\right), \tag{12}$$

and S_{Ti} by:

$$\mathbb{E}_{X_{\sim i}}\left[\mathbb{V}_{X_i}[Y \mid X_{\sim i}]\right] \approx \frac{1}{2N}\sum_{j=1}^{N} \left(f(A)_j - f(A_B^{(i)})_j\right)^2 \tag{13}$$

with A, B being $N \times k$ sample matrices of N samples of the k input factors X, and $A_B^{(i)}$ being a matrix, where column i is taken from sample matrix B whereas all other $k-1$ columns are taken from matrix A. In later application, the random vector X is given by the uncertain input parameters as specified in Table 2, whereas the role of the random variable Y is either taken by the net present value or the levelized cost of electricity, see Eqs. (7) and (9).

4. Results and discussion

We introduced a unique cost dataset for 19 SMR concepts of seven different reactor types including so-called advanced reactor technologies, land-based systems, and floating nuclear power plant concepts, and identified two main approaches to estimate costs for SMR concepts.

4.1. Cost estimates

Next, we identified a gap between construction costs as advertised by manufacturers and as estimated based on the Roulstone and Rothwell estimation theory and an α value between [0.20; 0.75] through computation of the costs for the 15 SMR concepts we had sufficient data available for reference reactors (see Fig. 1, data on the reference reactors can be found in Table 9 in Appendix B). This gap was, in general, larger for sodium–cooled reactors and smaller for pressurized water reactors and high-temperature reactors.

In general, for the PWR reactor concepts, manufacturer-advertised per MW construction costs first increased with the decrease of reactor capacity until a break for the NuScale and RITM 200M concepts before increasing again with lower capacities. The lower end of the theoretical per MW construction cost estimates are all in the same range, while the higher ends increased with the decrease in reactor capacity. Only the PWR SMR concept costs of the CAREM lie within the intervals of its cost estimates, yet, at the very low end.

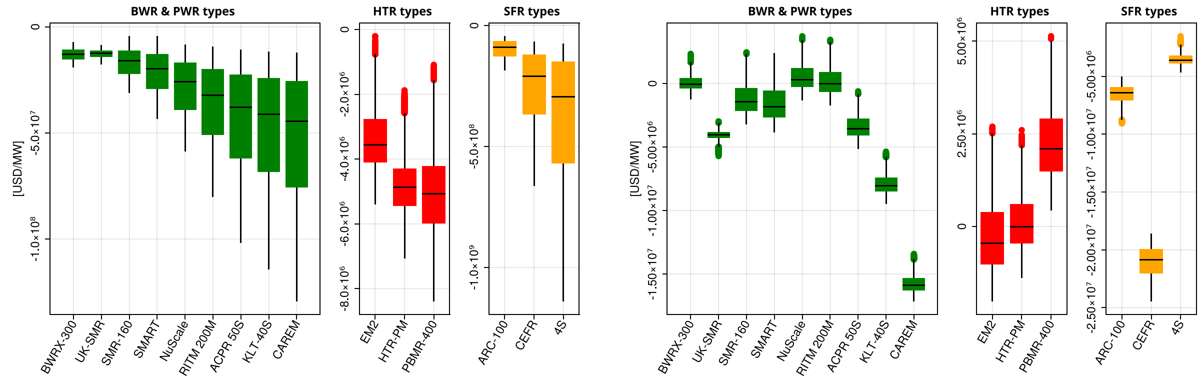
Interestingly, for the high-temperature reactors, per MW costs are the lowest in the simulation and, therefore, lower than for PWRs, which are based on technology well established in high-capacity reactors, while the gap is comparably small except for the PBMR-400 concept.

Costs for the sodium fast reactors are the highest with the largest intervals and with gaps being large with the exception of the CEFR, which has a gap similar to most of the PWR concepts.

4.2. Net present value

For the measurement of commercial success, we introduced the net present value, and the currently accepted cost measurement for the costs of electricity generation, the levelized costs. We constructed two best cases for construction costs, one for the structurally equal theoretical estimation approaches of Roulstone and Rothwell and one for manufacturer-advertised costs. In the theoretical case, we simulate uncertainty with the Monte Carlo technique for the parameter of investment costs estimated following Roulstone, average wholesale electricity price, the weighted average cost of capital, and the load factor. Since in the case of the advertised manufacturer costs the investment costs are deterministic, we simulate the uncertainty only for the average wholesale electricity price, the weighted average cost of capital, and the load factor. In all cases, we assume a construction period of three years.

For the net present value, the results were all negative in the theoretical approach (see Fig. 4(a) and Table 3) and almost always



(a) Roulstone cost estimation approach

(b) manufacturer advertised costs

Fig. 4. NPV boxplots of Monte Carlo simulation.

Table 3
Summary statistics for NPV simulations using the Roulstone estimation in USD_{2020}/MW_{el}.

Project	mean	std	min	q25	median	q75	max
BWRX-300	−13.169.436	2.748.514	−19.094.692	−15.454.395	−12.939.556	−10.779.885	−7.229.991
UK SMR	−12.679.348	1.803.058	−17.677.933	−14.154.594	−12.552.672	−11.146.416	−8.754.691
SMR-160	−16.921.583	6.506.864	−31.239.993	−22.129.297	−15.984.265	−11.282.241	−4.443.355
SMART	−21.396.212	9.824.956	−43.309.873	−29.101.727	−19.680.991	−12.845.275	−4.425.078
NuScale	−28.706.802	13.478.002	−58.772.507	−39.086.818	−25.976.675	−16.900.699	−8.339.690
RITM 200M	−36.542.415	19.090.769	−80.174.420	−50.949.842	−32.171.836	−19.857.896	−9.262.909
ACPR 50S	−43.890.249	24.561.466	−101.704.356	−62.018.893	−37.821.805	−22.537.086	−10.749.717
KLT-40S	−48.194.874	27.635.919	−114.326.369	−68.344.547	−41.097.354	−24.251.359	−11.724.234
CAREM	−53.005.654	31.628.292	−129.342.797	−75.809.286	−44.595.245	−25.663.217	−12.119.300
EM2	−3.392.312	887.031	−5.396.887	−4.096.084	−3.563.132	−2.765.298	−207.858
HTR-PM	−4.846.097	818.312	−7.062.408	−5.444.774	−4.870.789	−4.299.332	−1.877.259
PBMR-400	−5.070.456	1.240.089	−8.390.090	−5.986.227	−5.063.783	−4.216.214	−1.089.885
ARC-100	−97.577.507	37.678.495	−185.103.804	−126.882.327	−90.327.907	−64.472.737	−43.941.564
CEFR	−256.899.851	159.238.242	−663.233.116	−366.929.066	−209.652.719	−120.737.440	−66.994.740
4S	−387.793.663	283.206.228	−1.139.727.984	−570.471.203	−293.695.398	−149.988.258	−74.349.367

Table 4
Summary statistics for LCOE simulations using the Roulstone estimation in USD_{2020}/MWh.

Project	mean	std	min	q25	median	q75	max
BWRX-300	230	54	129	188	224	266	400
UK SMR	222	40	145	190	218	250	343
SMR-160	273	99	107	198	254	332	614
SMART	329	140	108	221	300	412	826
NuScale	414	187	133	267	371	524	1.088
RITM 200M	506	258	141	301	441	656	1.451
ACPR 50S	619	336	162	347	532	824	1.830
KLT-40S	672	376	169	368	572	901	2.042
CAREM	732	428	172	385	614	991	2.304
EM2	116	20	81	99	116	133	161
HTR-PM	136	22	94	117	134	153	193
PBMR-400	139	26	88	118	137	158	216
ARC-100	1.217	530	405	805	1.101	1.530	3.100
CEFR	3.484	2.244	733	1.648	2.805	4.861	11.662
4S	5.222	3.946	758	2.031	3.906	7.519	20.178

negative for the simulation for the manufacturer case (see Fig. 4(b)). Here, the only NPV from a pressurized water type concept delivering slightly positive results is the one of the American NuScale reactor with a median of 0.3 $mUSD/MW_{el}$ but with an interquartile range between −0.3 and 1.2 $mUSD/MW_{el}$. Only the high-temperature concept of the South African PBMR-400 exhibits a fully positive NPV with an interquartile range between 1.5 and 2.9 $mUSD/MW_{el}$ and a median of 2.1 $mUSD/MW_{el}$. This concept showed the biggest gap between cost estimation and manufacturer advertised costs among the HTR types, though (Fig. 1). Here it can be noticed, that the concept of the PBMR-400 has been postponed through financial constraints since 2009 and further cost increases for the NuScale project have been estimated since their uprate to 77 MW_{el}, which implies further licensing constraints and a significant likelihood that they will not operate as estimated with a 95% load factor when entering commercial service [58].

In general, theoretically estimated NPVs for HTR concepts exhibit interquartile ranges between −6.0 and −2.8 $mUSD/MW_{el}$ and median values between −3.6 and −5.1 mUSD/MW_{el} while BWR and PWR concepts have interquartile ranges one order of magnitude worse between −75.8 and −10.8 mUSD/MW_{el} with medians ranging from −44.6 to −16.6 mUSD/MW_{el}. SFR concepts are even farther from profitability with interquartile ranges between −570.5 and −64.5 mUSD/MW_{el} and median values between −293.7 and −90.3 mUSD/MW_{el}. Standard deviations show high uncertainties, especially for SFR concepts. For the manufacturer estimates, a few more concepts show profitability at the upper end of the interquartile range but values remain largely negative as well. The volatility is less marked with lower standard deviations due to the deterministic investment cost values.

4.3. Levelized cost of electricity

Next, we computed the LCOE based on the theoretical construction cost approach (see Fig. 5(a) and Table 4) and for the advertised manufacturer construction costs (see Fig. 5(b)) to be able to compare current levelized costs of SMR concepts with other electricity-generating technologies (e.g., cost of renewable energy sources). Here, the theoretical approach delivers higher levelized costs compared to the manufacturer model. In general, for the theoretical approach, cost minima are at 81 USD/MWh whereas the minimum costs in the manufacturer model are 56 USD/MWh, except the costs for the PBMR-400, which has been postponed through financial constraints since 2009.

Similar to the NPV analysis, the group of high-temperature reactors shows the lowest LCOEs with an interquartile range between 99 and 158 USD/MWh and comparably low standard deviations between 20 and 26 USD/MWh. The EM^2 exhibits the lowest median costs of all concepts at 116 USD/MWh. The concepts of the already established BWR and PWR technology types are in an interquartile range between 188 and 991 USD/MWh with a median between 224 and 614 USD/MWh but a standard deviation between 40 and 428 USD/MWh and therefore at costs just above the interquartile range of HTRs but with a significantly higher scattering and an increasing number of outliers of very high costs with a decrease in capacity. SFR-type reactor concepts can be found at LCOEs of one magnitude higher with an interquartile range between 805 and 7519 USD/MWh and a median between 1101 and 3906 USD/MWh. Especially the CEFR and the 4S are driving the variability with standard deviations of 2244 and 3946 USD/MWh, respectively.

In the manufacturer approach, the costs of Central Argentina de Elementos Modulares (CAREM) and the Russian floating nuclear power plant (KLT-40S) deliver the highest values for PWR concepts at medians of 269 and 173 USD/MWh, respectively, but the absolutely highest costs are exhibited by the SFR concept of the CEFR with 349 USD/MWh. The interquartile ranges for HTR concepts lie between 45 and 89 USD/MWh with medians between 48 and 79 USD/MWh. BWR and PWR concepts have interquartile ranges between 63 and 316 USD/MWh with medians between 70 and 269 USD/MWh. Again, SFR types exhibit the largest interquartile range between 109 and 386 USD/MWh and medians between 121 and 349 USD/MWh, but compared to the theoretical approach they are much closer to the ranges of the other types. Due to the deterministic nature of the manufacturer estimates, standard deviations in the simulation are significantly lower than for the theoretical estimates with values between 4 and 52 USD/MWh.

Furthermore, the costs to generate electricity seem to be non-competitive when compared to current costs for generating electricity from renewable energy sources (see Fig. 6). Even when considering necessary system integration costs for renewables, LCOEs only grow by a factor of two [59]. Long-run energy system modeling studies show a decrease of LCOEs, for example, for the case of Europe from 71 EUR/MWh in 2020 to a value below 50 or even 40 EUR/MWh depending on the scenario [60]. Another—and especially for variable renewables important—way of comparing electricity generation technologies is their market value since wind and PV do not always produce at times when needed in the system. Therefore, instead of the long-run production costs, their value weighted by the market price at the time of generation can be used for comparison. Currently, the market value is usually below their LCOE. Latest modeling shows, though, that with increasingly flexible energy systems the market value of renewables does not decrease significantly below their LCOE [61].

4.4. Sensitivity analysis

Looking at the results of the variance-based sensitivity analysis we can see that the variance of the simulated NPV is mainly explained by the fluctuations of the random investment cost given, in view of Eq. (2), via the sampled scaling parameters, whereas the electricity price and the load factor have almost no effect on the NPVs' variance (see Fig. 7(a)).[11] The values can be read as the percentage of the overall variance of the model outcome that can be attributed to the variance of a specific input factor. For most reactor concepts, the investment costs' variance is the main driver for variance in the outcome. High-temperature concepts are the exception with a higher weight on the WACC, for EM^2 this even being the main influence.

Comparing with Fig. 1, it can be seen that for the high-temperature SMR concepts (EM2, HTR-PM, and PBMR-400) the maximum cost intervals from which the random investment costs are drawn are relatively small. Consequently, these random variables have a smaller effect on the overall variance, allowing the influence of other random factors to become visible. The cause for these smaller intervals is that the power output of the reference reactor for HTRs is in the same order of magnitude compared to the SMR concepts. For non-HTR concepts, the WACC (and, in the case of the NPV, also the electricity price) play a larger role with an increase of the SMR power rating, i.e., the closer it gets to the power rating of the reference reactor.

Since the WACC is crucial for discounting (considering compound interest effects), its fluctuation is understandably significant in explaining the overall variance, provided that it is not masked by the investment costs. While for the NPV mainly the investment costs play a role, the WACC has a significantly larger influence on the LCOE as here also the electricity production is discounted.

For the LCOE simulations, the electricity price naturally does not affect the variance of the outcome (since it is not part of the estimation equation) but also the variance of the load factor has no significant contribution to the variance of the outcome (see Fig. 7(b)). Again, high-temperature reactors' LCOE variance is mostly driven by the WACC variance and less by investment variance. For most other concepts it is vice versa with a stronger influence from the investment cost variance for the fast reactor types (which also exhibit a lot of outliers at the higher end). The BWRX-300 and the UK-SMR are exceptions.

The simulations—including the sensitivity runs—required around 30 GB of RAM per scaling type and ran around 25 minutes on an AMD EPYC 7302 processor with 3 GHz in a high-performance computing cluster. The code developed for this paper is openly accessible on GitHub.[12]

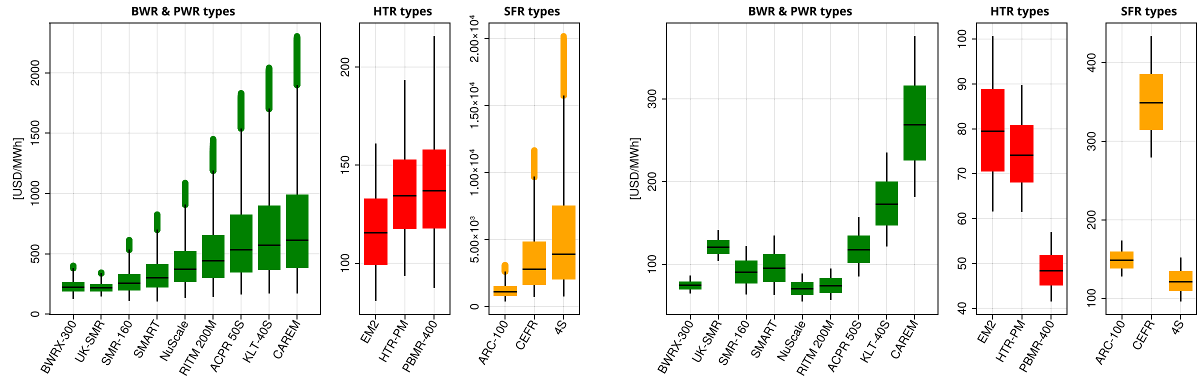
5. Conclusion

In this paper, we present different approaches to assess the economics of SMRs (small modular reactors), representing a technology still under development. We have identified different functional forms applied in the literature and assembled a large data set consisting of both producers' data and other publicly available data. We identified significant gaps between current cost estimations by theory applied in this paper and manufacturer-advertised costs.

Based on a large-scale Monte Carlo analysis of potential net present values (NPVs) and levelized costs of electricity (LCOE), we find that

[11] Notice that we rounded the results of the sensitivity analysis to two digits.

[12] https://github.com/weibezahn/smr-mcs



(a) Roulstone cost estimation approach

(b) manufacturer advertised costs

Fig. 5. LCOE boxplots of Monte Carlo simulation.

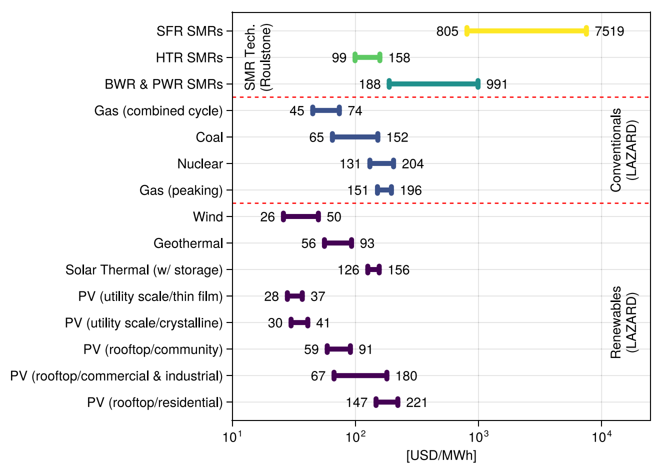


Fig. 6. LCOE comparison with other generation technologies based on Lazard [10]. Interquartile range shown for SMRs.

Table 5
Acronyms.

ARIS	Advanced Reactor Information System
BWR	Boiling water reactor
GFR	Gas-cooled fast reactor
HTGR	High-temperature gas reactor
HTR	High-temperature reactor
IAEA	International Atomic Energy Agency
LCOE	Levelized cost of electricity
LFR	Lead-cooled fast reactor
MR	Micro reactor
MSFR	Molten salt fast reactor
MSR	Molten salt reactor
NEA	Nuclear Energy Association
NPV	Net present value
OCC	Overnight construction costs
PRIS	Power Reactor Information System
PWR	Pressurized water reactor
SFR	Sodium-cooled fast reactor
SMR	Small modular reactor
TLCC	Total life-cycle cost
WNA	World Nuclear Association

SMR concepts do not seem to be an economic alternative to existing low-carbon technologies during our design lifetime simulation using the most favorable parameter values based on the literature. Even when using the overly optimistic manufacturer-advertised construction costs in the simulation, the majority of examined SMR concepts cannot deliver a positive NPV. The variance in the simulations can be in the largest part explained by the variance of the investment costs and the WACC, whereas the load factor and the electricity price play a minor role.

Future research needs to consider alternative functional forms and parameter choices for SMR concepts and provide a more nuanced differentiation of the technologies involved. Additionally, our assumption of only three years for the construction period should be further investigated.

Acronyms

See Table 5.

CRediT authorship contribution statement

Björn Steigerwald: Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing – original draft, Writing – review & editing. **Jens Weibezahn:** Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Martin Slowik:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Christian von Hirschhausen:** Conceptualization, Writing – original draft.

Declaration of competing interest

No author associated with this paper has disclosed any potential or pertinent conflicts which may be perceived to have impending conflict with this work.

Data availability

The data used is fully listed in the Appendix. The code used is openly available on GitHub at https://github.com/weibezahn/smr-mcs.

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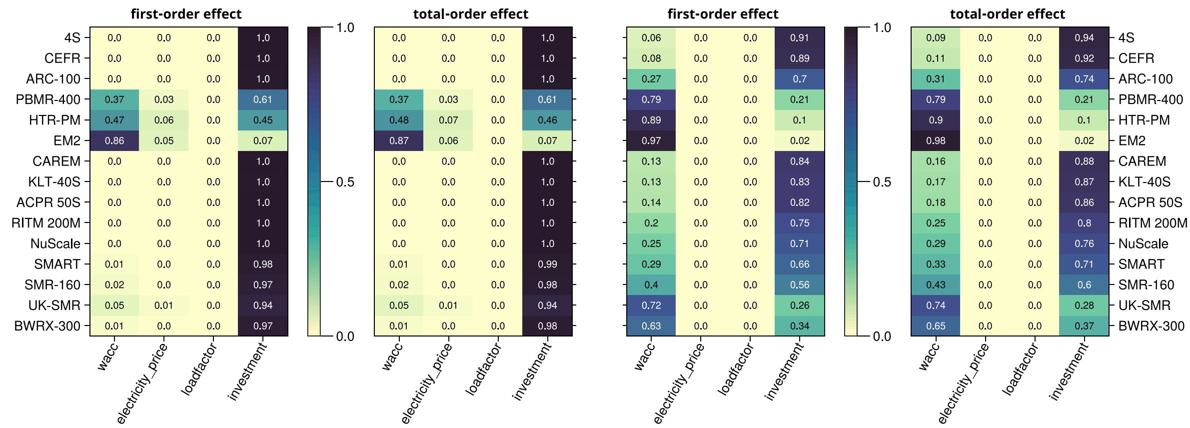

(a) NPV (b) LCOE

Fig. 7. Sensitivity indices of Monte Carlo simulation for Roulstone cost estimation approach.

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Appendix A. Short descriptions of SMR concepts

In this section, we briefly introduce included SMR concepts from our unique cost data set. For this, we divide this section into concept-corresponding reactor coolants (i.e., "water-cooled reactors" for describing concepts that are cooled with water, etc.) in the order of our data set. The information in this section is dated May 2023.

A.1. Water-cooled reactors

A.1.1. BWRX-300

A boiling water reactor (BWR), developed by General Electrics and Hitachi, with a capacity of 300 MW_{el}/870 MW_{th}. This concept is capable of using uranium oxide (UO2) or mixed oxide (MOX) as fuel. It represents the tenth generation of boiling water reactors developed by General Electric since 1955 (Dresden-1 (IL), and GE Vallecitos (CA)). This concept is based on the design of the Economic Simplified Boiling Water Reactor (ESBWR) with 1530 MW_{el}, certified in the US in 2014 [20,37]. This concept has been in NRC Pre-Application Review since 2019 and last submitted documents here in January 2021.[13]

A.1.2. UK SMR

A pressurized water-cooled reactor (PWR), developed by Rolls-Royce, with a capacity of 470 MW_{el}/1276 MW_{th}. This concept is using uranium oxide (UO2) as fuel [20,37]. The UK government has signaled financial support for the further development and certification of the UK SMR [62]. In 2023, Rolls-Royce calls for more clarity on nuclear development plans at a session of the House of Commons Welsh Affairs Committee.[14] The Project has currently finished the UK Generic Design Assessment (GDA) Phase 1 and is currently in Phase 2 [63].

A.1.3. SMR-160

An integral pressurized water reactor (PWR), developed by Holtec International, with a capacity of 160 MW_{el}/525 MW_{th}. This concept is using uranium oxide (UO2) as fuel and is related to the CAREM, mPower, NuScale, SMART, and Westinghouse SMRs. Development started in 2012 and certification is ongoing in the US and in Canada. The first criticality is currently planned for 2026 (the initial target was 2020) [20,37]. Holtec International has signed a cooperation agreement with the Ukrainian nuclear industry for joint production in Ukraine and the installation of up to 20 SMR-160 in the Rovno nuclear power plants.[15] This concept is in NRC Pre-Application Review since 2020 and last submitted documents here in January 2023.[16]

A.1.4. SMART

An integral pressurized water reactor (PWR), developed by the Korea Atomic Energy Research Institute in cooperation with the King Abdullah CARE (City for Atomic and Renewable Energy, Saudi Arabia), with a capacity of 107 MW_{el}/365 MW_{th}. This concept is using uranium oxide (UO2) as a fuel and is related to the CAREM, mPower, NuScale, SMR-160, and Westinghouse SMRs. The development of the SMART began in 1999 and the "Standard Design" was certified by the Korean nuclear safety authorities in 2012, the first prototype is scheduled for 2029 [20,37]. In 2023, the Korea Atomic Energy Research Institute (KAERI) signed a memorandum of understanding with the Government of Alberta to collaborate on the deployment of the Korean-designed SMART reactor - in the Canadian province.[17]

A.1.5. NuScale

An integral pressurized water reactor (PWR) developed by NuScale Inc., with a capacity of 77 MW_{el}/160 MW_{th}. This concept is using uranium oxide as fuel. There is currently a 12-module and a 6-module configuration in development (12 *x* 77 MW_{el} (= 924 MW_{el}). The engineering firm Fluor owns a majority share in NuScale, which is currently developing a prototype in cooperation with Idaho National Laboratories (INL). The first design and testing facilities were developed in 2003, the Design Certification Review was finished by the US NRC in 2020. First electricity deliveries to the local utility (Utah Associated Municipal Power Systems, UAMPS) are planned for 2027 [20,37]. Cooperation

[13] https://www.nrc.gov/reactors/new-reactors/smr/licensing-activities/pre-application-activities/bwrx-300.html
[14] https://www.energylivenews.com/2023/01/26/rolls-royce-calls-on-government-for-more-clarity-on-nuclear/
[15] https://www.world-nuclear-news.org/Articles/Accord-sees-mass-deployment-of-Holtec-SMRs-in-Ukra
[16] https://www.nrc.gov/reactors/new-reactors/smr/licensing-activities/pre-application-activities/holtec/documents.html
[17] https://www.world-nuclear-news.org/Articles/MoU-sees-KAERI,-Alberta-cooperation-on-SMRs

agreements have also been signed with companies in the US, Canada, Romania, the Czech Republic, Ukraine, Jordan, and Kazakhstan.[18]. The company itself joined forces in May 2022 with the Spring Valley Acquisition Corp to create the world's first and only publicly traded SMR technology provider, which will operate as NuScale Power Corporation.[19]

A.1.6. RITM 200M

An integral pressurized water reactor (PWR) for electricity and heat production with a capacity of ($50\,MW_{el}/175\,MW_{th}$) in maritime platforms. It is the follow-up design to the KLT-40S, also developed by JSC Afrikantov (Rosatom), and is based on previous generations of ice breakers. A prototype of the RITM 200M was installed on an ice breaker in the Arctic in 2016, and in 2021 six units were installed overall [20,37]. In 2021, Rosatom signed a long-term power supply take-or-pay contract with a subsidiary of Kaz Minerals for the usage of three floating nuclear power plants each employing a pair of the new 55 MW_{el} RITM-200M reactors for the new Baimskaya copper mining project in the Chukotka region of eastern Siberia with a start in 2022.[20] At the end of 2022, Shanghai-based Wison Heavy Industries got the contract to build the hull, which will be towed to Russia by the end of 2023 for reactor installation.[21]

A.1.7. ACPR 50S

A pressurized water reactor (PWR), by China General Nuclear Power Corporation (CGNPC) in cooperation with the China State Shipbuilding Corporation, for marine-based electricity and heat supply developed with a capacity of ($50\,MW_{el}/200\,MW_{th}$). This concept is fueled by uranium oxide (UO2). The first prototype was planned for 2021; at present, there are no recent updates in the trade media available [20,37].

A.1.8. KLT-40S

A pressurized water reactor (PWR) developed for a water-based platform for use in isolated areas developed by JSC "Afrikantov" (Rosatom). The reactor has a capacity of ($35\,MW_{el}/150\,MW_{th}$), using uranium oxide dispersion fuel. It is on the basis of previous designs for ice breakers. Update of previous designs started in 1998, construction started in 2007, and the first commercial application was launched in 2020, to be deployed in Pevek (East Siberia), the "Akademik Lomonossov". The KLT-40S will be replaced by the next generation of water-based reactors, the RITM series [20,37].

A.1.9. CAREM

An integral pressurized water reactor (PWR) developed by the Argentinian CNEA (Comission Nacional de Energia Atomica), with a capacity of ($30\,MW_{el}/100\,MW_{th}$). This concept uses uranium oxide (UO2) as fuel. Development work started in 1984 and the first partial construction permit was delivered in 2013 [20,37]. The construction started in 2014 and was continued in 2021.[22] At present, there are no new updates on the construction status in the trade media available.

A.2. High-temperature reactors

A.2.1. EM^2

The EM^2 concept is a helium-cooled fast-neutron high-temperature reactor developed by General Atomics with a capacity of ($265\,MW_{el}/500\,MW_{th}$). The project is designed to use uranium carbide as fuel with a design lifetime of 30 years without refueling to produce electricity and process heat. The reactor will be factory manufactured and transported to the plant site by truck [20,37]. General Atomics has a long-standing history of nuclear reactor development and has done pre-application activities for this project by the US NRC in 2021.[23]

A.2.2. HTR-PM

The HTR-PM is a high-temperature, gas-cooled pebble bed reactor developed by the Tsinghua University Institute of Nuclear and New Energy Technology (INET) with a capacity of ($210\,MW_{el}/2\ x\ 250\,MW_{th}$). This Reactor is using uranium-oxide TRISO fuel and is based on the HTR-10 research reactor, constructed in 1992. Early developments in these pebble-bed reactors, which are in part adapted to these SMR concepts, are Peach Bottom (USA) and the German AVR reactor. The HTR-PM is under development since 2001 [20,37]. The project has reached its initial full power with stable operation under the mode of two reactors with one machine in 2022.[24] The concept seems to be the demonstration plant for the finished design of the 600 MW_{el} multi-module HTR-PM600 nuclear power plant, which consists of six reactor modules or Nuclear Steam Supply System (NSSS) modules coupling to one steam turbine. Each NSSS module has the same design as the HTR-PM demonstration plant [37, p. 148].

A.2.3. PBMR-400

The PBMR-400 is a high-temperature, gas-cooled (helium) pebble-bed reactor for electricity and heat generation, using uranium-oxide TISO (sometimes also WPu-TRISO) as fuel. It was developed in South Africa based on technology transfer from the German AR reactor in Jülich. PBMR Pty is owned by Eskom, the South African state power company, which has long struggled to meet the growing demand for power in the country. The PBMR-400 was under development from 1993 until the first tests took place in 2009. The financial crisis in 2009 led to a halt in development–no further investors were found and a high-capacity reactor solution was not realized [20,64]. The literature mentions cooperation with scientists from Tsinghua University working on a similar high-temperature reactor concept for China.[25] In 2020 South African utility Eskom published a request for an Expression of Interest in reviving all or parts of the Pebble Bed Modular Reactor (PBMR) project and seeking investors to take stakes in PBMR Ltd, the development and deployment of the reactor design, and in TRISO fuel manufacturing.[26]

A.3. Sodium-cooled reactors

A.3.1. ARC-100

The ARC-100 is a classical sodium-cooled fast reactor to produce electricity and process heat, developed by Advanced Reactor Concepts (ARC, Canada), using uranium alloy as fuel. The concept has a planned capacity of ($100\,MW_{el}/286\,MW_{th}$) based on proven technology developed at the Experimental Breeder Reactor-II, which operated successfully at Argonne National Laboratory for 30 years. In 2019, the

[18] https://www.nuscalepower.com/en/projects
[19] https://www.world-nuclear-news.org/Articles/Completion-of-merger-creates-publicly-traded-SMR-c
[20] https://www.world-nuclear-news.org/Articles/Russia-commits-to-further-floating-nuclear-power-p
[21] https://www.nucnet.org/news/construction-begins-in-china-of-first-hull-for-baimskaya-minerals-deposit-9-4-2022
[22] https://www.world-nuclear-news.org/Articles/Construction-of-Argentinas-small-CAREM-25-unit-to
[23] https://www.nrc.gov/reactors/new-reactors/advanced/licensing-activities/pre-application-activities/genatom.html
[24] https://www.world-nuclear-news.org/Articles/China-s-demonstration-HTR-PM-reaches-full-power
[25] https://www.world-nuclear-news.org/Articles/Government-drops-final-curtain-on-PBMR
[26] https://www.world-nuclear-news.org/Articles/Eskom-seeks-interest-in-PBMR-commercialization

design completed the Canadian Nuclear Safety Commission's (CNSC) first phase of a vendor design review as a third advanced reactor.[27] The concept has been selected for deployment in New Brunswick, with a fully operational unit at the Point Lepreau nuclear site by 2029 besides the consideration of the Belledune Port Authority using an ARC-100 for the provision of energy for hydrogen production and other industries as part of a future expansion at the port in northern New Brunswick [20,37].[28]

A.3.2. CEFR

The Chinese Experimental Fast Reactor (CEFR) is a research reactor (20 MW_{el}) using MOX fuel (mixed plutonium-uranium) in a sodium-cooled fast reactor. It is developed by China Nuclear Energy Industry Corporation (CNEIC) as the pilot for the further industrial development of a 600 MW_{el} fast reactor (under development since 2017) and, ultimately, a 1000–1200 MW_{el} fast reactor. The CEFR has been operated quite irregularly since 2010, with a continuous operation of 40 days in 2020 [20,37]. In 2021, it is reported that the reactor has been restarted and reconnected to the grid, marking its entry into its high-power operation phase.[29]

A.3.3. 4S (super-safe, small and simple)

The 4S is an SMR concept of a sodium-cooled fast reactor developed by Toshiba Energy Systems & Solutions Corporation, Japan. The concept uses uranium-zirconium-alloys as fuel, to produce electricity and (high-temperature) heat in two design variants with a capacity of (10 MW_{el}/30 MW_{th}). Toshiba Energy developed it to be a "walk-away" reactor (installed underground) for a planned option period of 30 years without changing fuels. Pre-design certification was started in 2007 [20,37]. Brookfield Business Partners (BBP) purchased Westinghouse Electric Company from Japan's Toshiba Corporation in 2018 as the company emerged from bankruptcy proceedings.[30]

A.4. Molten-salt reactors

A.4.1. IMSR

The IMSR (Integral Molten Salt Reactor) is a graphite-moderated, fluoride-salt-cooled reactor using uranium-fluoride-salt as a fuel (potentially also plutonium- or thorium-fluoride salt) to produce electricity and heat with a capacity of (195 MW_{el}). The core module is exchanged every seven years. The ISMR is developed by Terrestrial Energy Inc. (Canada). The conceptual design was finished in 2015, and the production of a prototype reactor is planned for the mid-2020s [37]. The project completed the US and Canadian regulators' joint review in June 2022, where the Canadian Nuclear Safety Commission (CNSC) and the US Nuclear Regulatory Commission (NRC) agreed to cooperate in reviewing advanced reactor and small modular reactor (SMR) technologies.[31] In April 2023, the project passed the Canadian Vendor Design Review (VDR) with the result of no identified fundamental barriers to licensing the concept.[32] On the other hand, the US pre-licensing activities are ongoing with currently the topical report of 1"Principal Design Criteria for IMSR Structures, Systems, and Components" under review.[33]

A.4.2. SSR-W300

The SSR-W300 is a molten salt reactor with a capacity of (300 MW_{el}/750 MW_{th}) using fast neutrons to produce electricity and heat and to recycle spent fuel from light-water reactors, heavy water reactors (CANDU), and advanced gas-cooled reactors (AGR). The SSR-W300 uses fluoride salts as coolant, and uranium-plutonium fluoride salt as fuel (45% plutonium and actinides, 55% uranium). The conceptual design was finished in 2017, and since 2020 Moltex cooperates with the Canadian National Laboratory (CNL) and other partners to develop a site for reconverting spent fuels [20,37]. In May 2021, the project completed the Canadian Nuclear Safety Commissions' first phase of the pre-licensing vendor design review.[34] The Commission finds that there is a need for additional information in a future review.[35]

A.5. Lead-cooled reactors

A.5.1. BREST-OD-300

The Brest-OD-300 is a lead-cooled reactor developed by NIKIET with a capacity of (300 MW_{el}/700 MW_{th}). This concept is using mixed uranium-plutonium nitride as a fuel [20,37]. The construction of the project started in June 2021 at the site of the Siberian Chemical Combine (an enterprise of TVEL Fuel Company of ROSATOM) in Seversk, Russia's Tomsk region.[36] In August 2021, the concrete work for the foundation slab was finished[37] and in September 2022 the base plate for the reactor was delivered to site.[38] Currently, the assembly has begun for the prototype of the main circulation pump unit (MCPU) being built in Russia.[39]

A.6. Micro reactor

A.6.1. e-Vinci

Westinghouse's e-Vinci is a micro-reactor using TRISO particles in a reactor block, which transfers the heat to a power conversion unit (2-3.5 MW_{el}, electricity and heat). The modular units can be transported flexibly and run for three years before being hauled back to the point of departure. In late 2020, the project was awarded by the US Department of Energy (DOE) to receive USD 9.3 million of cost-shared funding (USD 7.4 million as the US Department of Energy's share) under the Advanced Reactor Demonstration Program (ARDP) to advance the design of the heat pipe-cooled microreactor.[40] In 2021, Westinghouse Government Services was awarded a DOE grant to develop a mobile micro-reactor for military purposes, the de-Vinci [20,37]. In February 2023, the major milestone of the production of a first 12-foot heat pipe at Westinghouse's Waltz Mill facility in Pennsylvania can be noted.[41] The project is in the US Nuclear Regulatory Commission (NRC) Pre-licensing process since October 2019 and met with the US NRC in May 2023 to discuss white papers related to the eVinci design.[42]

[27] https://www.world-nuclear-news.org/Articles/ARC-100-passes-Canadian-pre-licensing-milestone

[28] https://www.world-nuclear-news.org/Articles/New-Brunswick,-Saskatchewan-enhance-collaboration

[29] https://www.world-nuclear-news.org/Articles/Chinese-fast-reactor-begins-high-power-operation

[30] https://www.world-nuclear-news.org/Articles/Brookfield-sees-new-dawn-for-nuclear

[31] https://world-nuclear-news.org/Articles/US-and-Canadian-regulators-complete-joint-review-o

[32] https://www.world-nuclear-news.org/Articles/Terrestrial-SMR-completes-Canadian-pre-licensing-r

[33] https://www.nrc.gov/reactors/new-reactors/advanced/licensing-activities/pre-application-activities/imsr.html

[34] https://world-nuclear-news.org/Articles/MoltexFLEX-launches-flexibly-operated-molten-salt

[35] https://nuclearsafety.gc.ca/eng/reactors/power-plants/pre-licensing-vendor-design-review/moltex-energy-executive-summary.cfm

[36] https://rosatom.ru/en/press-centre/news/rosatom-starts-construction-of-unique-power-unit-with-brest-od-300-fast-neutron-reactor/

[37] https://world-nuclear-news.org/Articles/Foundation-set-in-place-for-BREST-reactor

[38] https://www.world-nuclear-news.org/Articles/Base-plate-for-BREST-reactor-delivered-to-site

[39] https://www.world-nuclear-news.org/Articles/Production-under-way-of-prototype-pump-unit-for-le

[40] https://www.world-nuclear-news.org/Articles/Major-component-manufacture-is-eVinci-milestone

[41] https://www.world-nuclear-news.org/Articles/Major-component-manufacture-is-eVinci-milestone

[42] https://www.nrc.gov/reactors/new-reactors/advanced/licensing-activities/pre-application-activities/evinci.html

Appendix B. Data & sources

B.1. SMR cost data

See Tables 6–8 for an overview of the used data set of SMR cost parameters for the 19 considered projects.

For the variable operation costs, we follow Cooper [76] and set the costs to 2.33 USD_{2020}/MWh_{el}.

B.2. Reference reactors for cost computation

See Table 9.

B.3. Additional reactor data

See Tables 10 and 11.

Table 6
Investment costs.

Project	Type	Investment cost [USD_{2020}/MW_{el}]	Source
BWRX-300	BWR	2,250,000	https://nuclear.gepower.com/content/dam/gepower-nuclear/global/en_US/documents/product-fact-sheets/BWRX-300_Fact_Sheet-2020.pdf
UK-SMR	PWR	5,215,937	https://world-nuclear-news.org/Articles/Rolls-Royce-on-track-for-2030-delivery-of-UK-SMR
SMR-160	PWR	6,312,500	https://holtecinternational.com/wp-content/uploads/2019/10/HTB-060-Holtecs-160-MWe-Nuclear-Reactor-Generic.pdf
SMART	PWR	8,000,000	https://neutronbytes.com/2020/01/18/south-koreas-smart-smr-gets-new-life/
NuScale	PWR	3,600,000	https://www.nuscalepower.com/en/news/press-releases/2020/nuscale-power-announces-an-additional-25-percent-increase-in-nuscale-power-module-output
RITM 200M	PWR	4,212,000	[65]
ACPR 50S	PWR	8,532,000	[65]
KLT-40S	PWR	13,531,429	https://bellona.org/news/nuclear-issues/2015-05-new-documents-show-cost-russian-nuclear-power-plant-skyrockets
CAREM	PWR	23,187,500	https://reneweconomy.com.au/small-modular-reactor-rhetoric-hits-a-hurdle-62196/
EM2	HTR/GFR	4,373,300	[66]
HTR-PM	HTR	3,270,000	[67]
PBMR-400	HTGR	1,734,300	[64]
ARC-100	SFR	5,050,000	https://www.reutersevents.com/nuclear/ebr-ii-experience-aided-arc-100-smr-design-review
CEFR	SFR	19,350,000	[68, p. 87]
4S	SFR	6,900,000	[69]
IMSR (300)	MSR	4,054,266	[70]
SSR-W	MSFR	1,950,000	https://inis.iaea.org/Search/searchsinglerecord.aspx?recordsFor=SingleRecord&RN=47073950
e-Vinci	MR	5,771,429	[71]
Brest–OD-300	LFR	4,160,000	https://tass.com/economy/1300401

Table 7
Fuel costs.

Project	Type	Fuel cost [USD_{2020}/MWh]	Source
BWRX-300	BWR	29.55	general average of all available values
UK-SMR	PWR	6.23	Technology-specific average
SMR-160	PWR	6.23	Technology-specific average
SMART	PWR	5.31	[72]
NuScale	PWR	7.15	[73]
RITM 200M	PWR	6.23	Technology-specific average
ACPR 50S	PWR	6.23	Technology-specific average
KLT-40S	PWR	6.23	Technology-specific average
CAREM	PWR	6.23	Technology-specific average
EM2	HTR/GFR	19.29	[66]
HTR-PM	HTR	13.96	Technology-specific average
PBMR-400	HTGR	8.63	[74]
ARC-100	SFR	78.04	Technology-specific average
CEFR	SFR	113.05	[75]
4S	SFR	23.86	[69]
IMSR (300)	MSR	8.94	[70]
SSR-W	MSFR	29.55	[10]
e-Vinci	MR	29.55	[10]
Brest–OD-300	LFR	29.55	[10]

Table 8
Operations & maintenance costs.

Project	Type	O&M cost [USD_{2020}/MW_{el}]	Source
BWRX-300	BWR	144,365	https://www.reutersevents.com/nuclear/ge-hitachi-chases-gas-plant-displacement-new-300-mw-reactor
UK-SMR	PWR	518,242	https://www.power-technology.com/news/uk-first-smr-rolls-royce/
SMR-160	PWR	146,645	Technology-specific average
SMART	PWR	65,025	[77]
NuScale	PWR	179,595	[73]
RITM 200M	PWR	170,980	set equal to previous concept KLT-40S
ACPR 50S	PWR	146,645	Technology-specific average
KLT-40S	PWR	170,980	[67]
CAREM	PWR	146,645	Technology-specific average
EM2	HTR/GFR	104,340	[66]
HTR-PM	HTR	168,920	[67]
PBMR-400	HTGR	136,630	Technology-specific average
ARC-100	SFR	130,750	[10]
CEFR	SFR	130,750	[10]
4S	SFR	130,750	[10]
IMSR (300)	MSR	180,512	[70]
SSR-W	MSFR	130,750	[10]
e-Vinci	MR	130,750	[10]
Brest–OD-300	LFR	130,750	[10]

Table 9
Reference reactor data.

Project	Type	Investment cost [USD_{2020}/MW_{el}]	Capacity [MW_{el}]	Source
Clinton-1	BWR	9,722,604	935	[78]
Vogtle-3	PWR	8,600,000	1,117	[9]
Fort St. Vrain	HTR	7,197,750	200	[78]
Superphénix	SFR	27,747,200	1,250	[79]

Table 10
Addional reactor data.

Country	Reactor	Type	Capacity [MW_{el}]	Investment cost [USD/kW_{2020}]	Source
USA	Clinton-1	(BWR)	935	9,723	[78]
USA	Hope-Creek	(BWR)	1,053	10,608	[78]
USA	Riverbend-1	(BWR)	919	8,974	[78]
FIN	Olkiluoto-3	EPR (PWR)	1,600	7,983	[55]
FIN	Olkiluoto-3	EPR (PWR)	1,630	5,733	[9]
FRZ	Flamanville-3	EPR (PWR)	1,600	9,270	[55]
FRZ	Flamanville-3	EPR (PWR)	1,600	8,620	[9]
UK	Hinkley Point C-1	EPR-1750	1,630	8,549	[55]
UK	Hinkley Point C-2	EPR-1750	1,630	8,549	[55]
USA	Vogtle-3	AP1000	1,117	11,330	[55]
USA	Vogtle-4	AP1000	1,117	11,330	[55]
USA	Vogtle-3	AP1000	1,117	8,600	[9]
USA	Vogtle-4	AP1000	1,117	8,600	[9]
KOR	Shin Kori 3	APR1400	1,340	2,410	[9]
KOR	Shin Kori 4	APR1400	1,340	2,410	[9]
CHI	Sanmen-1	AP1000	1,000	3,154	[9]
CHI	Sanmen-2	AP1000	1,000	3,154	[9]
CHI	Taishan-1	EPR (PWR)	1,660	3,222	[9]
CHI	Taishan-2	EPR (PWR)	1,660	3,222	[9]
RUS	Novovoronezh II-1	VVER1200 (PWR)	1,144	2,244	[9]
RUS	Novovoronezh II-2	VVER1200 (PWR)	1,144	2,244	[9]
USA	Fort St. Vrain	(HTGR)	200	7,195	[78]
USA	Fort St. Vrain	(HTGR)	200	8,108	[80]
USA	Peach Bottom-1	(HTGR)	46	1,197	[81]
RUS	Beloyarsk-3	BN-800 (SFR)	880	2,501	[82]
FRZ	Superphénix	(SFR)	1,250	27,747	[79]

Table 11
Additional operations & maintenance costs.

Reactor type	Country	O&M cost [USD_{2020}/MW_{el}]	Source
EPR	France	14,26	[83]
ABWR	Japan	25,84	[83]
OPR/APR	Korea	18,44	[83]
VVER440	Slovakia	9,72	[83]
ALWR	USA	11,60	[83]
ALWR, EIA	USA	19,18	[83]
CPR/HPR	China	26,42	[83]
PHWR/VVER	China	23,84	[83]
VVER	Russia	10,15	[83]
Long Term Operation (LTO)	Switzerland	12,92	[84]
Long Term Operation (LTO)	France	12,92	[84]
Long Term Operation (LTO)	Sweden	12,92	[84]
Long Term Operation (LTO)	USA	18,69	[84]
EPR, new-build	France	14,26	[84]
ALWR, new-build	Japan	25,84	[84]
ALWR, new-build	Korea	18,44	[84]
VVER, new-build	Russia	10,15	[84]
Other, new-build	Slovakia	9,72	[84]
LWR, new-build	USA	11,60	[84]
LWR. new-build	China	26,42	[84]
LWR, new-build	India	23,84	[84]
Conventional Nuclear		23,69	[85]

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