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# Challenges of small modular reactors: A comprehensive exploration of economic and waste uncertainties associated with U.S. small modular reactor designs

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ABSTRACT

This article presents a comprehensive analysis and review of the levelized cost of electricity (LCOE) and nuclear waste generation from small modular reactors (SMRs) designed in the United States. The analysis presented here offers a perspective on the uncertainties surrounding the calculation of LCOE for SMRs. Initially, the paper discusses and calculates the capital costs, front-end fuel cycle costs, operating and maintenance expenses, and nuclear waste production of four distinct types of SMRs—boiling light water, pressurized light water, high-temperature gas-cooled, and sodium fast reactor types— based on designs by four different manufacturers in the United States. Our review and analysis indicate there is considerable uncertainty in LCOE estimations of SMRs, particularly emphasizing that non-light water designs are likely to be more expensive in fuel cycle costs and have greater uncertainties in nuclear waste management compared to light water reactor designs. This comprehensive analysis of SMRs significantly broadens our understanding of their economic complexities and the implications these pose for deployment in the foreseeable future. Lastly, our estimates suggest that both SMRs and large nuclear reactors will require revolutionary approaches to reduce the capital cost overruns to be cost competitive with other energy sources.

Nomenclature

| Nomenclature | Description | Unit |
|---|---|---|
| $OCC_{SMR,types,MWe}$ | Overnight capital costs for different types of small modular reactors | US $/MWe |
| $OCC_{Reference,types,MWe}$ | Overnight capital costs for different types of reference reactors | US $/MWe |
| $P_{SMR,types,MWe}$ | Reference unit power for different types of small modular reactors | MWe |
| $P_{Reference,types,MWe}$ | Reference unit power for different types of reference reactors | MWe |
| $FC_{SMR,types,initial\ load}$ | Initial core load fuel cycle costs for different types of small modular reactors | US$ |
| $FC_{SMR,types,annual}$ | Annual refueling fuel cycle costs for different types of small modular reactors | US$ |
| $C_f$ | Capacity factor | % |
| $FC_{Mining\&Milling,types}$ | Cost of uranium mining and milling for different types of small modular reactors | US$ |
| $FC_{Conversion,types}$ | Cost of uranium conversion for different types of small modular reactors | US$ |
| $FC_{Enrichment,types}$ | Cost of uranium enrichment for different types of small modular reactors | US$ |
| $FC_{Fabrication,types}$ | Cost of fuel fabrication for different types of small modular reactors | US$ |
| $FC_{Depleted,types}$ | Cost of deconversion and disposal of depleted uranium for different types of small modular reactors | US$ |
| $M_{Mining\&Milling,types}$ | Mass of uranium required for mining and milling for different types of small modular reactors | kgU |
| $M_{Conversion,types}$ | Mass of uranium required for conversion in different types of small modular reactors | kgU |
| $SWU_{Enrichment,types}$ | Separative work units required for uranium enrichment in different types of small modular reactors | |
| $M_{Fabrication,types}$ | Mass of uranium required for fuel fabrication in different types of small modular reactors | kgU |
| $M_{Depleted,types}$ | Mass of depleted uranium for different types of small modular reactors | kgU |

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| | | |
|---|---|---|
| $M_{Natural\ Uranium,types}$ | Mass of natural uranium required for different types of small modular reactors | kgU |
| $UC_{Mining\&Milling,types}$ | Unit costs of uranium mining and milling for different types of small modular reactors | US $/kgU |
| $UC_{Conversion,types}$ | Unit costs of uranium conversion for different types of small modular reactors | US $/kgU |
| $UC_{Enrichment,types}$ | Unit costs of uranium enrichment for different types of small modular reactors | US $/SWU |
| $UC_{Fabrication,types}$ | Unit costs of fuel fabrication for different types of small modular reactors | US $/kgU |
| $UC_{Depleted,types}$ | Unit costs of deconversion/disposal of depleted uranium for different types of small modular reactors | US $/kgU |
| $O\&M_{SMR,types,MWe}$ | Operation and maintenance costs for different types of small modular reactors | US $/MWe |
| $O\&M_{Reference,types,MWe}$ | Operation and maintenance costs for different types of reference reactors | US $/MWe |
| $CRF$ | Capital recovery factor | |
| $D$ | Discount rate | % |
| $T_L$ | Years during which the cost is amortized | yr |
| $n$ | Scaling factor | |

## 1. Introduction

Since the 2000s, nuclear power's share of total global production has been declining. In the late 1990s, it accounted for around 18 % of global electricity generation, but by 2023, it has fallen to about 9 % (IEA, 2025). This is partly due to the fact that nuclear energy became more expensive due to its high construction costs and long construction periods while other energy sources became cheaper over time, as previous studies have shown (IEA, 2020; Lazard Ltd, 2021; OECD/NEA, 2020; Rothwell, 2022; Steigerwald et al., 2023). The decline in energy share especially in the United States (U.S.) and Europe since 1995 is attributed to uncertainties in cost recovery within deregulated markets, prolonged completion schedules for the latest Western nuclear power plant designs, and escalating construction costs (Rothwell, 2022). According to recent estimates from the Lazard report, the unsubsidized levelized cost of electricity (LCOE) for nuclear energy in the U.S. ranges from \$141/MWh to \$221/MWh (Lazard Ltd, 2023), surpassing that of both renewables and conventional energy sources.

Meanwhile, several countries that are newcomers to nuclear energy, such as Egypt, Bangladesh, and Türkiye, are currently in the process of constructing their first large nuclear power plants (all Russian designed VVER reactors). In the face of challenges encountered by the nuclear industry in competing with renewables and natural gas, coupled with opportunities in newcomer countries, the nuclear industry has begun to advocate for the potential of small modular reactor (SMR) designs. Accordingly, many countries have accelerated the development of SMRs, with China recently beginning commercial operation of its own SMR (HTR-PM). In response, the U.S. has seen the emergence of many new SMR companies, a few receiving substantial support from the government (Thomas and Ramana, 2022). For example, in the current light water reactor (LWR) landscape, NuScale promotes its pressurized water reactor (PWR) design (NuScale Power Module), while GE-Hitachi is marketing a boiling water reactor (BWR) design (BWRX-300). Beyond these conventional LWR type reactors, there are advanced designs such as a sodium-cooled fast reactor (SFR) (Natrium designed by TerraPower) and a high-temperature gas-cooled reactor (HTGR) (Xe-100 designed by X-energy) (GE Hitachi Nuclear Energy, 2023; International Atomic Energy Agency, 2024a; Kim et al., 2022). Table 1 provides a comparison of these reactors.

However, the primary concern regarding SMRs revolves around their economic feasibility in comparison to large LWRs—as well as other energy sources. The issue of economic feasibility came into focus, following the termination of a planned NuScale SMR power plant project in the U.S. (NuScale, 2023a). NuScale had engaged with Utah Associated Municipal Power Systems (UAMPS), a coalition of utilities, to construct the 12 NuScale reactors in Idaho. However, rather than proceeding with the already certified design (50 MWe), NuScale submitted an application to the U.S. Nuclear Regulatory Commission for a larger, more cost-effective reactor model (77 MWe) (Table 1). Moreover, construction plans recently encountered upheaval when the reactor's cost surged to \$9.3 billion, an increase of about \$4 billion from the original estimate of \$5.3 billion (Penn and Plumer, 2023). In the end, UAMPS and NuScale mutually agreed to terminate the UAMPS project (Gardner and Mishra, 2023).

In line with these concerns, many studies show that the economics of SMRs will be much costlier than that of large LWRs, thereby will not be competitive or profitable. For example, Steigerwald et al. (2023) have estimated the median levelized cost of electricity (LCOE) as over \$200/MWh for general PWR SMR types, which is much higher compared to other energy sources (i.e., gas combined cycle as \$45–74/MWh, wind as \$26–50/MWh, and rooftop solar–community as \$59–91/MWh (Lazard Ltd, 2021)). The Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) estimated that the LCOE for future SMRs would range between AU\$198–349/MWh in 2030, AU\$117–399/MWh in 2040, and AU\$117–401/MWh in 2050 (Graham et al., 2023). However, their updated report revised the estimates upward to AU\$230–382/MWh in 2030, AU\$171–366/MWh in 2040, and AU\$172–349/MWh in 2050 (Graham et al., 2024). Stewart and Shirvan (2022) also showed that for a First-of-a-Kind (FOAK) reactor, the capital cost estimate of SMRs remains higher than that of the Large Passive Safety PWR (similar to the AP1000), while Nth-of-a-Kind (NOAK) SMRs may experience cost reductions but do not necessarily become less expensive than a NOAK Large Passive Safety PWR. In another example, the targeted overnight construction costs of the SMART SMR, designed by South Korea, is projected at \$10,000/kWe (International Atomic Energy Agency, 2020), which is about four times higher than the cost of the APR1400 (a large LWR designed by South Korea, \$2,410/kWe in 2018 US\$ from 2020 data (Rothwell, 2022; Stewart and Shirvan, 2022). Additionally, a recent study has revealed that SMRs can produce more nuclear waste per energy unit compared to large LWRs, challenging future waste disposal and management (Krall et al., 2022).

Predictions of SMR generation costs are highly subjective, characterized by significant uncertainty, and heavily dependent on the specific literature under consideration. Here, we comprehensively review, analyze, and estimate the costs of SMRs, specifically four distinctive nuclear reactor types (BWRX-300, NuScale Power Module, Xe-100, and Natrium). We estimate the LCOE using overnight capital cost projections, fuel cycle costs (front-end cycle), and operation and

**Table 1**
Comparison of SMR designs.

| | BWRX-300 | NuScale Power Module | Xe-100 | Natrium |
|---|---|---|---|---|
| Reactor type | Boiling water reactor (BWR) | Pressurized water reactor (PWR) | High temperature gas-cooled reactor (HTGR) | Sodium fast reactor (SFR) |
| Power (MW) (Thermal/ Electrical) | 870/300 | 250/77 | 200/80 (or 82.5) | 840/345 |
| Manufacturer | GE-Hitachi | NuScale | X-energy | TerraPower |
| Design life (years) | 60 | 60 | 60 | 60 |
| Fuel type/ assembly array | $UO_2$/ Square lattice | $UO_2$/17 × 17 square | TRISO particles (UCO)/ Pebbles | Metallic Uranium Alloy/ Hexagonal |
| Fuel enrichment (%) | 3.81 (average)/ 4.95 (maximum) | ≤4.95 | 15.5 | 19.75 (maximum)/ 16.5 (demonstration) |

**Table 2**
Value of economy of scale exponent.

| Study | *n* value |
|---|---|
| Carelli et al. (2010) | [0.5; 0.7] with an average value of 0.6 |
| OECD/NEA (2011) | [0.45; 0.6] with an average value of 0.51 |
| Steigerwald et al. (2023) | [0.20; 0.75] with using Monte Carlo simulation |
| Froese et al. (2020) | 0.55 |

maintenance (O&M) costs. We further discuss the uncertainties regarding the calculation of these costs and review the specific wastes from each reactor type because these can significantly influence waste management and decommissioning costs for particular SMR designs.

This study contributes to existing literature by providing a comprehensive analysis of LCOE and delving into the intricacies and inherent uncertainties in LCOE calculations for SMRs. While several studies have explored SMR LCOE, they often relied on assumptions without offering detailed explanations and exposing their limitations. Our study distinguishes itself by encompassing the full scope of SMR LCOE and addressing factors that may impact overall costs of these technologies, despite the inability to determine precise calculations. Our contribution extends beyond technical considerations to embrace a policy perspective. This study explores the challenges that the U.S. has encountered in the commercialization of SMRs, with a focus on non-LWR types (HTGR and SFR), including an examination of nuclear fuel fabrication, the back-end of the fuel cycle, and decommissioning.

The remainder of this study proceeds as follows. Section 2 reviews and calculates capital, fuel cycle and O&M costs, including an analysis of uncertainties in the calculations. Section 2 also introduces and reviews nuclear waste streams from each SMR type. In section 3, we calculate the LCOE for different types of SMRs and compare them with a reference large LWR, the Westinghouse AP1000. Finally, in Section 4, we conclude with policy implications.

## 2. Background methodology

### 2.1. Capital costs

#### 2.1.1. Overnight capital costs

In the LCOE of nuclear power, capital costs usually stand out as the most significant portion. Identifying the overnight capital costs of SMRs is, therefore, important in calculating the LCOE of SMRs. While opinions vary on the effects of co-siting, learning, construction schedule, and modularization on the overnight capital costs of SMRs in several studies, many analysts believe that SMR overnight capital costs will basically follow economies of scale, known to engineers for decades (Mignacca and Locatelli, 2020; Ramana, 2021). Historically, the growth in generating capacity of nuclear reactors has been driven by non-linear scaling of capital and operating costs, reflecting material and labor demands. As such, SMRs are anticipated to incur higher costs per unit of output (Carelli et al., 2010). Despite debates against applying this principle to today's SMR designs, due to their significant design divergence from existing large reactors, the concept of economic disadvantages due to smaller size persists.

In this study, the economy of scale is solely used to calculate overnight capital costs, leveraging recent studies' data for each reactor type.

$$OCC_{SMR,types,MWe}\left[\frac{\$}{MWe}\right] = OCC_{Reference,types,MWe}\left(\frac{P_{SMR,types,MWe}}{P_{Reference,types,MWe}}\right)^{n-1} \quad (1)$$

The equation of economy of scale is represented in Eq. (1). The $n$ represents the scaling factor, which is reported to range from 0.2 to 0.75 (Carelli et al., 2010; Froese et al., 2020; OECD/NEA, 2011; Steigerwald et al., 2023), dependent on the specific SMR project. The different $n$ values for each previous study are shown in Table 2. In this study, we followed the scale value $n = 0.6$, similar to Carelli et al. (2010) for simplicity.

To compute the FOAK overnight capital costs, we considered various overnight construction cost ranges of reference reactors, covering both low and high case values (see Table 3). In analyzing the overnight capital costs of four different types of FOAK SMRs, we used the economy of scale equation as a reference for the costs of each distinct type of historical reactor, including a large BWR, PWR, HTGR, and SFR. To do this, we first selected Vogtle Unit 3 (a recently-operating PWR in the U.S.), THTR-300[1] (an HTGR in Germany, shutdown in 1988), and Superphénix (an SFR in France; shutdown in 1998), all of which were FOAKs in their countries, as a reference costs. As a low case value, we set the original/initial overnight capital cost data for these three distinct types of previous commercial/prototype reactors, as provided in previous publications (Dixon et al., 2017; Rothwell, 2022). For the high case value, a recent study (Eash-Gates et al., 2020) showed a doubling in costs for major facilities at plants between 1976 and 2017. As a result, to determine the high case values, we doubled the reference capital cost. However, it is essential to note, as stated by Eash-Gates et al. (2020), that these cost overruns may vary within standard designs, due to unforeseen escalations arising from design differences across reactor types. Nevertheless, we typically presumed an approximate doubling of cost for the HTGR and the SFR for the high case value of the historical overnight capital cost (THTR-300 and Superphénix), considering their construction started in the 1970s. Cost overruns of FOAK reactors in the U.S. have doubled in the case of Vogtle Units 3&4, with the initial estimate of $14 billion escalating to over $35 billion (Amy, 2023a).

For the BWR case, however, the BWRX-300 is based on an Economic Simplified BWR (ESBWR) rather than a traditional BWR design. There are no large ESBWRs in operation to date. As a result, we were compelled to adopt GE-Hitachi's ESBWR proposed overnight capital cost as the low case value. Virginia Power estimated the cost of building one ESBWR to be $8,593/kWe in 2015 US$ (which corresponds to about $11,085/kWe in 2023 US$) (Schlissel, 2016). For the high case value of ESBWR, an Institute for Energy Economics and Financial Analysis study concluded that ESBWR reactors will be about 10–15 % more expensive than AP1000 reactors (Schlissel, 2016). Therefore, we multiplied by factor 1.15 to obtain the high-end estimate for the overnight capital costs of the AP1000 ($14,700/kWe (IEA, 2025)), which corresponds to the high-end estimate for the ESBWR.

There are still other uncertainties in calculating the overnight capital costs of SMRs and additional challenges that can contribute to an increase in the capital costs of SMRs. These challenges are discussed in the following sub-section.

#### 2.1.2. Discussion of the uncertainties and challenges of estimating overnight capital costs

In this section, we look into other uncertainties, including those related to economies of scale and other factors such as the learning rate, construction schedule, and modularization. As suggested by the SMR industry, these factors can mitigate the lack of economy of scale found in SMRs and contribute to reducing their overnight capital costs. Our focus is on the historical cases (in the U.S. and Europe) to examine whether these factors genuinely contribute to lowering the final capital costs.

*2.1.2.1. Economy of scale.* It is undeniable that there can be uncertainty in extrapolation using economies of scale to estimate the overnight capital cost of SMRs, which typically includes direct and indirect costs (Shirvan, 2022). Direct costs include reactor components and power production systems, while indirect costs are categorized into engineering services, construction services, and special equipment expenses

[1] We selected THTR-300 as the reference reactor for the overnight capital costs of Xe-100 due to its pebble bed core design, which aligns with Xe-100's. While Fort St. Vrain supplied more electricity than THTR-300 and was built in the U.S., it used a prismatic core. However, we also acknowledge that THTR-300 used a thorium-uranium fuel mixture, which differs from Xe-100's fuel.

**Table 3**
Overnight capital cost reference.

| Reactor type | Reference reactor | Reference reactor power (MWe) | Low case of overnight capital cost (2023 US$/kWe) | High case of overnight capital cost (2023 US$/kWe) | Reference |
|---|---|---|---|---|---|
| BWR | ESBWR (GE-Hitachi) | 1,520 | 11,085 | 16,905 | Schlissel (2016) |
| PWR | Vogtle-3 | 1,117 | 10,406[a] | 14,700[b] | (IEA, 2025; Rothwell, 2022) |
| HTGR | THTR-300 | 296 | 24,140 | 48,280 | Dixon et al. (2017) |
| SFR | Superphénix | 1,200 | 13,394 | 26,787 | Dixon et al. (2017) |

[a] For example, we adjusted initial AP1000 project overnight capital costs from $8,600/kWe (Rothwell, 2022) in 2018 US$ to reflect an overnight capital cost in 2023 US$. All inflation adjustments from historical US$ values to 2023 US$ were made using the U.S. Inflation Calculator (https://www.usinflationcalculator.com). For consistency, we derived year-specific conversion factors by determining how much US$1 from each historical year would cost in 2023 and applied these to all historical cost figures. Detailed conversion factors and original overnight capital cost estimates for the reference reactors are presented in the Appendix and Supplementary Materials.

[b] The IEA (2025) reported a capital cost estimate for Vogtle of US$14,700/kWe in 2023 US$.

(Shirvan, 2022; Vegel and Quinn, 2017). Evaluating the reference dataset using only economies of scale may increase cost uncertainty by ignoring the fact that each individual component of direct and indirect cost may not follow the same exponent value of economies of scale. To make the results more reliable, economies of scale should be applied to individual direct and indirect components (Vegel and Quinn, 2017), rather than the overall estimate we used. Nevertheless, since previous studies so far have used only economies of scale in the construction of basic overall overnight capital costs (Froese et al., 2020; Steigerwald et al., 2023), we have done so based on these previous studies to simplify the calculations. However, we admit that applying a uniform exponent value ($n = 0.6$) across all SMR types introduces coarse approximations, especially given the technological diversity of SMR designs, and that the absence of probabilistic uncertainty analysis limits the robustness of our cost estimates. Stochastic approaches such as Monte Carlo simulations could potentially offer a more rigorous representation of the uncertainty associated with cost scaling and input variability.

With that said, in the case of operational SMRs in China, economies of scale exist, as the capital cost of SMRs eventually surpassed that of large LWRs. Although precise overnight capital cost data for China is unavailable, according to the World Nuclear Association, the construction cost for the FOAK HTR-PM is around $6,000/kWe (World Nuclear Association, 2023a), about twice the average overnight capital cost in China for large LWRs, which is approximately $3,188/kWe (Rothwell, 2022).

*2.1.2.2. Historical overnight capital cost references for non-LWR reactors.* To calculate overnight capital costs, we used the overnight capital costs for four different types of prototype/large commercial reactors, provided in the literature (Dixon et al., 2017; IEA, 2025; Rothwell, 2022; Schlissel, 2016). However, there a lot of uncertainties about using this reference data themselves.

First, we acknowledge the variation in the reported overnight capital costs across different studies and reports (National Academies of Sciences Engineering and Medicine, 2023a). In the case of Superphénix, we adopted the value reported by Dixon et al. (2017). However, we observed significant discrepancies in values reported by other peer-reviewed articles. For instance, Lovering et al. (2016) estimated the cost at $8,533/kWe in 2010 US$, while Steigerwald et al. (2023) reported $27,747/kWe in 2020 US$. These variations arise due to the lack of official data and differences in the exchange rate application methods used in each cost estimation. Overnight capital cost estimates can vary significantly depending on the choice of reference reactor; using a different reference could lead to different extrapolated values.

Second, it remains unclear whether the cost data being used truly represent overnight capital costs. In our study, for example, we used the reference AP1000, THTR-300, and Superphénix project/investment costs as overnight capital cost references (Dixon et al., 2017; IEA, 2025; Rothwell, 2022); however, these costs are not explicitly overnight capital costs. Obtaining reliable overnight cost references is challenging since the cost estimates are not publicly available. Moreover, it remains uncertain whether excluding financing charges from the overnight capital cost for calculating LCOE is appropriate. Interest costs significantly influence the total direct costs of nuclear power plants, representing an average of 46 % of the total initial costs of reactors in the U.S. (Gilbert et al., 2017). Given that nuclear power plants are not built overnight, a number of analysts argue that they should be assessed based on overall construction costs rather than solely on overnight capital costs (Gilbert et al., 2017; Koomey and Hultman, 2007), because with construction times extending beyond a decade in many cases, the cost of interest on the cost of construction can become a significant cost factor.

Using historical overnight capital costs for FOAK non-light water reference reactors entails significant uncertainties. For example, although we have used the overnight capital cost of the THTR-300, this plant faced numerous issues, including problems with the fuel circulation system, leading to intermittent shutdowns and repairs, culminating in a final shutdown due to damage in the gas ducts (Thomas, 2011). Additionally, the THTR-300 encountered various technical challenges inherent to its pebble bed design, such as damaged fuel pebbles, graphite dust formation, and core bottom insulation failure due to overheating (Theymann, 1992; Thomas, 2011). This experience is similar to that of the Fort St. Vrain reactor, a representative HTGR (prismatic type) in the U.S., faced poor electrical generation due to prototype-related issues with small failures (Ramana, 2016), mainly helium circulators, leading to increased operational, maintenance, and fuel costs (Brey, 1991). This financial strain prompted the decision to shut down the Fort St. Vrain reactor prematurely, after only 10 years in service. Given these experiences in Germany and the U.S., the anticipated HTGR reference cost may significantly exceed our current estimation, which solely factors in inflation rates (especially if regulatory review requires the use of a containment building).

Moreover, like the HTGR, there are no currently operating commercial reactors of the SFR type in the U.S.; however, smaller demonstration/experimental units like Fermi-I[2] and Experimental Breeder Reactor (EBR)-II operated in the past, while the Clinch River Breeder Reactor Project (CRBR) in the 1970s and 1980s remained in the design stage and was terminated in 1983 (Cochran et al., 2009). Previous experience with Superphénix reveals its notably poor operational performance due to numerous technical issues (Schneider, 2009; Sun et al., 2024). Additionally, Phénix, the predecessor of Superphénix in France,

[2] Fermi-1 was designed by consortium of utilities, but its operation was ultimately considered a failure. It was shut down in 1972.

also encountered several sodium leaks, fires, and a series of potentially severe reactivity incidents (Aoto et al., 2014; Schneider, 2009). In light of this, future SFRs will likely require stricter safety regulations and systems, leading to the possibility of increased overnight capital costs than the previous construction costs of Superphénix.

*2.1.2.3. Construction time delays of FOAK reactors.* Many SMR manufacturers estimate a construction timeframe of about three to five years (Mignacca and Locatelli, 2020; Vegel and Quinn, 2017). The shorter construction period will lead to significant cost savings in capital expenditures by reducing interest costs (Budnitz et al., 2018). Nevertheless, it is evident that numerous construction delays occur on a regular basis for FOAK SMRs. For example, the KLT-40s, Russia's pioneer SMR that was placed on a barge, was initially projected to be delivered in four years (NS Energy, 2010), but ultimately took a staggering 13-years (Pioro et al., 2020). Although China is known to achieve nuclear power plant construction durations shorter than the global median (Eash-Gates et al., 2020), even the HTR-PM reactor (China's inaugural SMR) necessitated nearly a decade for completion (World Nuclear News, 2021).

The construction delays can be examined through the historical experience of large LWRs. Within the U.S., Vogtle Unit 3, a standardized AP1000 reactor, embarked on construction in 2009 (Clifford, 2023) but encountered prolonged timelines, exceeding a decade in construction duration. Originally projected for operational status by 2017, delays pushed its electricity production to reach 100 % in May 2023 (Amy, 2023b). Vogtle Unit 4's start date was delayed from the first quarter of 2024 to the second quarter due to a motor fault in one of four reactor coolant pumps (World Nuclear News, 2023).

Delays can also be seen in recent new builds in Europe. For example, the two French-design evolutionary power reactor (EPR) builds have been far over budget and schedule. The EPR in Finland (Olkiluoto-3) was originally supposed to cost €3 billion and open in 2009, with construction starting in 2005 (IEA, 2025; Ruuska et al., 2011; Weibezahn and Steigerwald, 2024). It finally began commercially producing electricity in 2023 at a cost of €11 billion (International Atomic Energy Agency, 2024b; Siddi and Silvan, 2024). There is a similar story in France, where the EPR at Flamanville was set to begin operation in 2012 at a cost of about €3 billion (Locatelli and Mancini, 2012; Ruuska et al., 2011). Instead, it encountered a huge construction delay and was connected to the national grid in December 2024. Costs for the Flamanville reactor have ballooned to over €13 billion (Électricité de France, 2022; Weibezahn and Steigerwald, 2024), over four times the expected costs, with long construction delays. Électricité de France (EDF) and the United Kingdom Government announced updates to the October 2013 agreement regarding the £16 billion investment contract for the Hinkley Point C (OECD/NEA, 2015). However, in 2024, EDF estimated the cost to be between £31 billion and £34 billion at 2015 prices (World Nuclear News, 2024a), potentially rising to over £46 billion at today's prices (Jack, 2024), with the project unlikely to be operational before 2030.

Construction delays can result in higher costs for labor, materials, and equipment, which are components of the overnight capital cost, as well as increased financing charges and interest expenses, ultimately contributing to higher overall construction costs. In light of the challenges encountered within Western countries, therefore, there exists a landscape marred by myriad uncertainties, signaling that SMR projects might not escape the pervasive pattern of construction time overruns, which can directly influence the overnight capital cost and final capital costs including interest costs resulting from construction delays.

*2.1.2.4. Modularization.* Many designers plan to build SMRs in factories to avoid some of the drawbacks of large reactor construction, appealing to factory fabricated modules for shorter construction times (Budnitz et al., 2018; Carelli et al., 2010). However, the example of the Vogtle project, involving building AP1000 reactors in factories, serves as a cautionary tale for SMR modularization and factory-fabricated reactors in the U.S.

The AP1000 design incorporates modular elements, and Westinghouse aimed to enhance cost competitiveness by improving quality and schedule flexibility in reactor construction through the utilization of modular construction technology (Matzie, 2008). Despite these efforts, the adoption of modularization did not lead to a significant price reduction for the Vogtle project—just the opposite: it resulted in schedule delays and significant cost overruns (Hals and Flitter, 2017). The contract for the modular design was first awarded to the Shaw Modular Solutions plant in Lake Charles, Louisiana, but inspections shortly after the plant began operations uncovered problems and errors, including poor welds. Problems at the Lake Charles plant persisted for years and resulted in the need to reweld the modules after delivery to the Vogtle site (National Academies of Sciences Engineering and Medicine, 2023a). Welding issues, other quality control issues, as well as safety culture problems continued through two new owners of the Lake Charles module fabrication plant, Chicago Bridge and Iron, which took over from Shaw, and then Westinghouse itself. By 2017, Westinghouse had declared bankruptcy (Moffett and Youngdahl, 2017).

*2.1.2.5. Learning rate.* The SMR industry expects that cost escalation due to diseconomies of scale and cost overruns from construction delays will be compensated by the experience gained from manufacturing numerous units, called learning rates. Manufacturers advocate for standardizing SMR components and reducing unit size to replicate factory production and leverage lessons from previous unit construction and deployment, resulting in lower costs of capital cost/LCOE for NOAK plants compared to FOAK plants (Budnitz et al., 2018; Carelli et al., 2010; IAEA Advanced Reactors Information System, 2019; Mulder, 2021a).

Despite substantial investments in research and development directed towards standardized designs and increased production, there remain uncertainties about the actual impact of these efforts on the reduction of capital costs. Historical data in the U.S. and France, the countries with the largest number of nuclear reactors, show an increase in reactor construction costs over time (Rubin et al., 2015). In the U.S., specifically, previous studies (Eash-Gates et al., 2020; Koomey and Hultman, 2007) indicate that even with increased construction experience—even NOAK plants based on standard reactor technology in the U.S.—have experienced cost escalation, challenging the belief that standardization inherently minimizes expenses. Eash-Gates et al. (2020) suggest that the reason for cost escalation is due to the lower labor productivity and soft costs (i.e., home office engineering services, temporary construction facilities, payroll insurance, and taxes). They also showed that plants of the same design could face common idiosyncratic effects; in addition, these reactors are often not identical, and disparities in other aspects of plant design can lead to unforeseen cost increases (Eash-Gates et al., 2020). In line with U.S. experience, in France, where a significant number of reactors with similar designs were constructed, discernible learning effects were limited or conditional, and in some cases, negative learning effects were found to occur (Berthélemy and Rangel, 2015; Grubler, 2010; Rangel and Lévêque, 2015).

Even assuming a positive learning rate, a significant number of SMRs would need to be constructed before they could begin to compete with large LWRs (Glaser et al., 2015; Ramana and Ahmad, 2016), creating a classic chicken-and-egg problem. Lowering the costs of SMRs through learning effects requires a substantial number of orders, but currently, there are no countries outside of China and Russia that have operational SMRs on offer or are placing bulk orders for SMRs, given the uncertainties surrounding their economic viability and demand levels.

This complexity could be further compounded by potential weaknesses and pitfalls in standardized design, creating unforeseen cost spikes. Despite historical trends, various stakeholders including the nuclear industry, governments, and other supporters persist in expecting

**Table 4**
Fuel cycle characteristic of different SMR types used for cost calculations.[a]

| Description | BWRX-300 | NuScale Power Module | Xe-100 | Natrium |
|---|---|---|---|---|
| Power (MWe) | 300 | 77 | 80 | 345 |
| Initial core load (kgU) | 44,760 | 9,269 | 1,540 | 21,260[b] |
| Numbers of bundles/ assemblies/pebbles in the core | 240 bundles | 37 assemblies | 220,000 pebbles | Lack of information |
| Uranium enrichment (% U-235) | 3.81 (average) | 4.95 | 15.5 | 16.5 |
| Refueling interval | 12 months | 18 months | Everyday | 18 months |
| Refueling characteristics | 32 bundles are replaced following a 12-month cycle | Nominal three-batch in an "in-out" shuffle scheme | 173 fresh pebbles are added and extracted daily | Lack of information |
| Charge (kgU) per bundle/ assembly/pebble | 186.5 | 251 | 0.007 | Not specified |
| Total refuelings per lifetime | 60 | 40 | 21,900 (Every day for 60 years) | 40 |
| Annual amount of refueling (kgU) | 5,968 | 2,060 | 442 | 2,001[c] |
| References | GE Hitachi Nuclear Energy (2023) | (International Atomic Energy Agency, 2024a, 2022; NuScale Power, 2022) | (International Atomic Energy Agency, 2024a, 2022; Mulder, 2021b) | (Hejzlar, 2021; Kim et al., 2022; Neider, 2021) |

[a] Fuel cycle parameters used in this study reflect data available at the time of writing and are subject to change as reactor designs evolve. For example, we applied a 16.5 % enrichment for the Natrium demonstration reactor based on publicly available academic and vendor sources (Hejzlar, 2021; Kim et al., 2022), as detailed estimates for the initial core load were unavailable. In contrast, International Atomic Energy Agency (2024a) lists a "maximum enrichment of 19.75 %" (see Table 1). Such discrepancies are expected and justifiable, given that many SMRs remain in the design or licensing phase.
[b] Due to the lack of information on the Natrium reactor, we relied on the initial core load data from Kim et al. (2022).
[c] Due to the lack of information, we generally calculated using the formula: 5.8 MTU/GWe-yr × 0.345 GWe = 2,001 kgU/yr. The 5.8 MTU/GWe-yr data is sourced from (Hejzlar, 2021; Neider, 2021).

cost decreases in future despite historical evidence of cost increases for past reactors.

In our calculations, we did not factor in a learning rate because we assumed a FOAK SMR in estimating the overnight capital costs. However, it is unclear whether the NOAK will be much cheaper than the FOAK, considering historical experience.

**Table 5**
Equations for the front-end nuclear fuel cycle cost calculation.

| Category | Equation | Eq. |
|---|---|---|
| Total cost of front-end fuel cycle | $FC_{SMR,types} = FC_{Mining\&Milling,types} + FC_{Conversion,types} + FC_{Enrichment,types} + FC_{Fabrication,types} + FC_{Depleted,types}$ | (4) |
| Cost of uranium mining & milling | $FC_{Mining\&Milling,types} = M_{Mining\&Milling,types} \times UC_{Mining\&Milling,types}$ | (5) |
| Cost of uranium conversion | $FC_{Conversion,types} = M_{Conversion,types} \times UC_{Conversion,types}$ | (6) |
| Cost of uranium enrichment | $FC_{Enrichment,types} = SWU_{Enrichment,types} \times UC_{Enrichment,types}$ | (7) |
| Cost of fuel fabrication | $FC_{Fabrication,types} = M_{Fabrication,types} \times UC_{Fabrication,types}$ | (8) |
| Cost of deconversion and disposal of depleted uranium | $FC_{Depleted,types} = M_{Depleted,types} \times UC_{Depleted,types}$ | (9) |
| Quantity of separative work unit for enrichment process | $SWU_{Enrichment,types} = \left[V(p) + \frac{p-f}{f-t} \times V(t) - \frac{p-t}{f-t} \times V(f)\right] \times M_{Fabrication,types}$, where $V(x)$ is a value function explained below | (10) |
| Value function | $V(x) = (2x-1)\ln\frac{x}{1-x}$ | (11) |
| Mass of natural uranium [a] | $M_{Natural\ Uranium,types} = \frac{p-t}{f-t} M_{Fabrication,types}$ | (12) |
| Mass of depleted uranium | $M_{Depleted,types} = M_{Natural\ Uranium,types} - M_{Fabrication,types}$ | (13) |
| Mass of uranium required for conversion | $M_{Conversion,types} = M_{Natural\ Uranium,types}$ | (14) |
| Mass of uranium required for mining and milling | $M_{Mining\&Milling,types} = M_{Natural\ Uranium,types}$ | (15) |

[a] p: fuel enrichment (%), t: tail assay (0.25 %), and f: feed assay (0.71 %).

## 2.2. Fuel cycle costs

### 2.2.1. Front-end fuel cycle cost analysis

In order to calculate fuel cycle costs, we separated costs into two categories: the initial core load cost and the annual refueling fuel cycle cost. Since we could not calculate the back-end fuel cycle costs (which will be discussed in the next sub-section), we generally calculated only the front-end nuclear fuel cycle (mining & milling, conversion, enrichment, and fuel fabrication) costs.

Table 4 outlines the mass and enrichment levels of fuel for the lifetime of the plant, based on available information (GE Hitachi Nuclear Energy, 2023; Hejzlar, 2021; International Atomic Energy Agency, 2024a, 2022; Kim et al., 2022; Mulder, 2021b; Neider, 2021; NuScale Power, 2022). The total front-end fuel cycle cost was computed by aggregating uranium mining & milling, conversion, enrichment, and fuel fabrication expenses, using the equilibrium model formula from previous studies (Asuega et al., 2023; Kim et al., 2015; Park et al., 2011). The detailed explanation of calculating initial core load/annual refueling fuel-cycle costs of each reactor type is explained in our Supplementary Materials. The equations that we have used are explained in Table 5. We defined $M_{Fabrication,types}$ values as the mass of the initial core load/annual refueling of each reactor type. The unit costs of each nuclear fuel cycle process are obtained from the reports (Idaho National Laboratory, 2023a, 2023b, 2023c, 2021a, 2021b, 2021c, 2021d), as outlined in Table 6. We assumed that there is no material loss during each nuclear fuel cycle process. The initial core load fuel cycle cost was calculated as a unit of \$/MWe, and the annual refueling fuel cycle cost was calculated as a unit of \$/MWh, as shown in Eqs. (2) and (3). We set capacity factor ($C_f$) as 90 % for all reactors.

$$\text{Initial core load cost}\left[\frac{\$}{\text{MWe}}\right] = \frac{FC_{SMR,types,initial\ load}}{P_{SMR,types,MWe}} \tag{2}$$

$$\text{Annual refueling cost}\left[\frac{\$}{\text{MWh}}\right] = \frac{FC_{SMR,types,annual}}{365 \times 24 \times C_f \times P_{SMR,types,MWe}} \tag{3}$$

### 2.2.2. Discussion of the uncertainties in fuel cycle costs

While (Idaho National Laboratory (2023a, 2023b, 2023c, 2021a, 2021b, 2021c, 2021d) has provided meticulous and detailed future cost estimates for mining to high-assay low-enriched uranium (HALEU)

**Table 6**
Front-end fuel cycle unit cost (in 2020 US$).

| Module | Description | Lower | Maximum | Reference |
|---|---|---|---|---|
| A1 ($UC_{Mining\&Milling.types}$) | Natural Uranium Mining and Milling ($/kgU) | 35.8 | 310.2 | Idaho National Laboratory (2021a) |
| B ($UC_{Conversion.types}$) | Conversion ($/kgU) | 6 | 17.9 | Idaho National Laboratory (2021b) |
| C ($UC_{Enrichment.types}$) | Enrichment ($/SWU)-Low enriched uranium (LEU) | 126 | 164 | Idaho National Laboratory (2023a) |
| | Enrichment ($/SWU)- high assay low enriched uranium (HALEU) for Category-II facility[a] | 144.9 | 188.6 | Idaho National Laboratory (2023a) |
| D ($UC_{Fabrication.types}$) | LWR-PWR $UO_2$ fuel fabrication ($/kgU) | 242 | 605 | Idaho National Laboratory (2023b) |
| | LWR-BWR $UO_2$ fuel fabrication ($/kgU) | 300 | 605 | Idaho National Laboratory (2023b) |
| | TRISO-based for any reactor concept fabrication ($/kgU) | 1,000 | 9,000 | Idaho National Laboratory (2021c) |
| | Never-irradiated 10–20 % U-235 HALEU-metal fuel fabrication ($/kgU) | 1,111 | 1,515 | Idaho National Laboratory (2023c) |
| K ($UC_{Depleted.types}$) | Deconversion of Depleted UF6 to Depleted Uranium Oxides ($/kgU) | 4.54 | 9.1 | Idaho National Laboratory (2021d) |
| | Geologic Disposal of Depleted Uranium Oxides ($/kgDU) | 4.5 | 45.3 | Idaho National Laboratory (2021d) |

[a] Assuming a 15 % cost increase for Category-II HALEU SWU compared to LEU SWU.

enrichment Category-II fuel fabrication, upon which we rely in this study, it is important to acknowledge that even these values are subject to significant uncertainties. In these following sub-sections, we discuss these uncertainties in the fuel cycle cost values of SMRs.

*2.2.2.1. Enrichment and fuel fabrication for high-assay low-enriched uranium.* The development of novel non-LWR reactor types in the U.S., exemplified by projects like Xe-100 and Natrium, requires HALEU enriched in U-235 to over 15 %, a resource exclusively supplied by Russia at present, and now, for U.S. companies, out of reach as a result of the Prohibiting Russian Uranium Imports Act of 2024.

The U.S. Department of Energy (DOE) has actively championed the HALEU program since the late 2010s to bolster energy security. Accordingly, the DOE initiated a request for proposals for uranium enrichment services in January 2024 (United States Department of Energy, 2024a). The Inflation Reduction Act allocated up to $500 million for HALEU enrichment contracts to be selected by the DOE's Office of Nuclear Energy, which plans to grant one or more contracts for the production of HALEU utilizing domestic uranium enrichment capabilities (United States Department of Energy, 2024a). In May 2024, President Biden signed the Prohibiting Russian Uranium Imports Act, banning U.S. imports of unirradiated LEU from Russia starting August 13, 2024, and unlocking $2.72 billion for U.S. LEU production, contingent on the ban per the Emergency National Security Supplemental Appropriations Act (United States Department of Energy, 2024b).

However, the nation's commercial enrichment capabilities face a challenging status. The U.S. is currently experiencing a sharp decline in U.S. uranium enrichment supply capacity, plummeting from 27.3 million SWUs annually in 1985 to about 4.7 million SWUs in 2020 (Day, 2022).[3] This decline underscores the pressing need to bolster domestic enrichment capabilities for the U.S. to maintain nuclear energy independence. U.S.-based Centrus' CEO highlighted the difficulties of the HALEU supply chain in the U.S., emphasizing the chicken-and-egg situation between who would purchase U.S. reactors using HALEU if the HALEU supply is not guaranteed and who would invest in the HALEU supply infrastructure if there is no significant demand (National Academies of Sciences Engineering and Medicine, 2023b).

In November 2022, the U.S. DOE provided $150 million to support the AC100M cascade demonstration and HALEU production. As a result of the Phase 1 project, the U.S. produced its first 20 kg of HALEU by the end of 2023. However, achieving the Phase 2 goal of producing 900 kg of HALEU annually by November 2024 is delayed due to the lack of 5B cylinders needed for UF6 storage (World Nuclear News, 2024b). The domestic supply chain for nuclear fuel, including HALEU, remains challenging.

Furthermore, our analysis did not separately account for the cost of HALEUF6 deconversion. Unlike oxide fuel for commercial light water reactors, which undergoes deconversion during the fuel fabrication process, advanced reactors using HALEU require various chemical forms of nuclear fuel, such as metal or oxide, depending on the developer's design. These require the development of new deconversion technologies and facilities. As a result, in November 2023, the U.S. DOE issued a Request for Proposals (RFP) for an Indefinite Delivery/Indefinite Quantity (IDIQ) contract to provide deconversion services for HALEUF6 into the specific chemical forms required for non-light water SMR fuels (Nuclear Newswire, 2023). In 2024, TerraPower and Framatome North America agreed to develop a HALEU metallization pilot line in Washington to demonstrate Framatome's HALEU metallization capability (Framatome, 2024). As of October 2024, the U.S. Department of Energy awarded 10-year contracts to six companies (BWXT, Centrus, Framatome, GE Vernova, Orano, and Westinghouse) to support the domestic supply chain for HALEU by providing deconversion services, with a total of up to $800 million available (United States Department of Energy, 2024c).

Another uncertainty associated with fuel cycle costs is that of fuel fabrication. There are no commercial nuclear fuel fabrication facilities for producing TRISO or metallic fuels. Specifically, there are no commercial Category-II fuel fabrication facilities established in the U.S. yet (National Academies of Sciences Engineering and Medicine, 2023b). As such, non-LWR SMR companies are working on domestic, commercial-scale fuel fabrication plants. In 2021, X-energy and Centrus Energy Corporation revealed the completion of the preliminary design phase for X-energy's TRISO-X Fuel Fabrication Facility (X-energy, 2021). In 2022, X-energy selected the Horizon Center Industrial Park in Oak Ridge, Tennessee, as the site for the commercial TRISO-X fuel manufacturing facility and submitted the first-ever license application for the TRISO-X Fuel Fabrication Facility to the Nuclear Regulatory Commission (NRC) (X-energy, 2022). As of the writing of this paper in 2023, the NRC reports that the review is 45 % complete (X-energy, 2023).

TerraPower and its partners are targeting the construction of a new metal fuel manufacturing facility specifically tailored to meet the demands of the Natrium fuel supply. In 2022, GNF-A and TerraPower revealed their intentions to construct a Natrium fuel fabrication facility adjacent to GNF-A's current fuel plant in the vicinity of Wilmington, North Carolina (Nuclear Newswire, 2022).

Estimating the actual commercial fuel fabrication costs for non-LWR types involves significant uncertainties. For instance, the available fuel fabrication cost data for TRISO fuels from the 1960s Fort St. Vrain HTGR fuel production pilot plant near San Diego, California is insufficient to determine current TRISO fuel fabrication costs. All ongoing TRISO fuel

[3] Urenco's New Mexico plant, licensed by Louisiana Energy Services, is owned by URENCO, which is equally held by three parties: the government of the United Kingdom, the government of the Netherlands, and German utilities.

fabrication activities in the U.S. are presently at the 'bench scale' (Idaho National Laboratory, 2021c). In 2023, Framatome Inc. and Ultra Safe Nuclear Corporation announced that they signed an agreement to establish a joint venture to begin manufacturing TRISO particles starting in 2026 (Ultra Safe Nuclear Corporation, 2023). Regarding metal fuel for SFRs, a significant challenge arises from the lack of large-scale production of metal-fuel types in the U.S., resulting in a scarcity of data for fuel cycle cost analysis (Idaho National Laboratory, 2023c). Moreover, according to the Natrium reactor design concept proposed by TerraPower, the goal is to develop and commercialize advanced metallic fuel (Type 1B fuel) that does not use sodium bonding (i.e., Type 1 fuel based on previous experience with sodium-bonded designs in fast reactors) but rather utilizes mechanical bonding (Hejzlar, 2021; Neider, 2021). While TerraPower aims to use sodium-bonded fuel initially in a Natrium plant with an average enrichment of Type 1 fuel (with 18.5 % and 59, 000MWd/THM), the ultimate objective is to certify and use advanced Type 1B fuel in the power plant (with 150,000MWd/THM) (Hejzlar, 2021; National Academies of Sciences Engineering and Medicine, 2023b; Neider, 2021). Their subsequent shift to a metallic fuel form without sodium bonding may require additional studies, potentially increasing uncertainties in fuel fabrication costs for the Natrium reactor.

*2.2.2.2. Back-end of the fuel cycle: Spent nuclear fuel volume and non-LWR fuels.* While we could calculate the ballpark front-end fuel cycle cost of each SMR type based on the Idaho National Laboratory analysis, it is difficult to determine the back-end fuel cycle costs—such as the conditioning, packaging, interim wet/dry storage of spent nuclear fuel (SNF) for SMRs with different types of fuel and their final disposal.

There is no study accurately estimating the back-end fuel cycle costs of various types of SMRs. As an alternative approach, a previous study, for example, has calculated the fuel cycle costs for different SMR types by assuming identical wet/dry storage and disposal costs regardless of the fuel type (Asuega et al., 2023). However, this assumption does not consider the limitation that disposal costs for various fuel types, especially non-LWRs, may differ significantly from those of conventional LWR fuels.

Preparation for the back-end fuel cycle of non-LWR SNF will require considerable effort, given the distinct nature of that SNF compared to that of LWRs. This disparity raises significant uncertainties in the costs associated with the back-end fuel cycle. The estimates of the volume of spent pebbles from Xe-100 is about 118 $m^3$/GWe-yr (Kim et al., 2022), which is significantly higher than the other three types of SMRs. Researchers found that decay heat and radiotoxicity for Xe-100 SNF is lower than for LWR SNF due to low heat density, effective heat transfer properties of TRISO particles and graphite, higher burnup, and thermal efficiency (Atz et al., 2024; Kim et al., 2022). In addition, a recent study asserted that though an HTGR generates significantly more SNF volume than other reactor types, its lower decay heat density enables tighter package spacing, reducing the repository footprint (repository area per package and per GWe-y in consideration of thermal constraints) (Wainwright et al., 2024).[4] But this study (Wainwright et al., 2024) did not consider the effects of HALEU on criticality considerations in storage and disposal. The challenge, however, lies in the volume for handling, transportation, and storage, and while pebble treatment for volume reduction could be possible, it is not required and may be undesirable due to added risk and cost (Atz et al., 2024). Moreover, the feasibility and implications of directly disposing of large volumes of spent pebbles (without extracting the TRISO particles from graphite pebbles) is not yet known (National Academies of Sciences Engineering and Medicine, 2023b), which will translate to a higher uncertainty in back-end fuel cycle costs.

Similarly, the SNF volume of SFR (Natrium) is estimated between $5.56\, m^3/GWe-yr$ to $6.72\, m^3/GWe-yr$ and mass between $5.93t/GWe-yr$ to $6.10t/GWe-yr$ (Atz et al., 2024; Kim et al., 2022) which is lower compared to the LWR types due to higher burnup and thermal efficiency. The important thing is, however, that direct disposal of HALEU sodium metal-fuel to a geologic repository is likely not possible and processing of this spent fuel will be required prior to disposal (Krall et al., 2022; National Academies of Sciences Engineering and Medicine, 2023b).[5] Considering that the Natrium demonstration plant will initially employ Type 1 fuel (sodium-bonded fuel) (Hejzlar, 2021; National Academies of Sciences Engineering and Medicine, 2023b; Neider, 2021), the existence of elemental sodium in sodium-bonded SNF typically inhibits its direct disposal in a geological repository, requiring sodium deactivation or removal (Idaho National Laboratory, 2007). To date, three treatment options under consideration are pyroprocessing, melt-drain-evaporate-carbonate (MEDEC), and alcohol wash, each with distinct considerations regarding waste form stability and implications for different geologic repository environments. Pyroprocessing, the most technically advanced of the three methods, is currently utilized for EBR-II SNF treatment, while MEDEC and alcohol wash processes require further exploration and testing for practical application (Atz et al., 2024). Nonetheless, no commercial operational pyroprocessing plants exist. Pyroprocessing unit cost estimates entail significant variability and uncertainty. In one recent study, Kim et al. (2023) projected that the unit cost for a pyroprocessing facility with the capacity of 400tHM was calculated as about $1,700/kgHM in 2020 US$ in South Korea. An Idaho National Laboratory (2021e) report, however, suggests probability distributions for the unit costs of integrated pyroprocessing separation and remote refabrication range from $2,850/kgHM to $7,100/kgHM in 2020 US$. That being said, post-treatment of SNF fuel of SFR type still has cost uncertainty, which can lead to potential cost overruns in the back-end fuel cycle.

To make the matters worse, the comparative advantages and economic viability of reprocessing versus direct disposal of SNF have been extensively discussed and contested. For example, Bunn et al. (2005) have demonstrated that the once-through LWR fuel cycle is anticipated to persistently undercut the costs of closed or partially closed cycle alternatives in both LWRs and fast reactors. A Massachusetts Institute of Technology (2011) study pointed out that, in comparing the LCOE among the different fuel cycles, the fast reactor cycle using reprocessing was the most costly, while the once-through cycle was the least costly. In India, though the cost of reprocessing SNF is lower than the Western countries, it is still higher than direct disposal (Ramana and Suchitra, 2007). A study by Kim et al. (2015) using the deterministic method, showed that a pyroprocessing-SFR nuclear fuel cycle was costlier than that for direct disposal, whereas the probabilistic method indicated the opposite. The bottom line is that any processing of these spent fuels will result in additional costs to the overall reactor lifetime.

Lastly, it is best for SNF to be stored and disposed of in a subcritical configuration to prevent the possibility of sustaining a fission chain reaction (Krall et al., 2022). However, there exists a potential risk due to the high concentration of fissile isotopes in HALEU SNF, particularly evident in non-light water SMRs (Krall et al., 2022). As such, back-end processing facilities may be essential for producing stable waste forms and maintaining subcriticality, dissipating decay heat prior to transport to a centralized facility or a geologic repository (Atz et al., 2024). Innovative approaches to container design and loading strategies, therefore, need to be demonstrated that mitigate the risk associated with back-end disposal. These may include using significantly more canisters and requiring larger volumes of storage space to achieve safe storage and disposal, all of which could significantly impact waste management and disposal costs. In summary, significant uncertainties and the potential for cost overruns exist in non-light water SMR spent fuel

[4] The results are not based on Xe-100.

[5] In this study, we only considered the once-through fuel cycle of all fuel types. We did not consider any reprocessing fuel cycle in non-LWR types.

**Table 7**
O&M cost reference data.

| Reactor type | Reference capacity (MWe) | Total annual O&M costs per year (US$ at reference year) | References |
|---|---|---|---|
| LWR (BWR and PWR) | 1117 (AP1000) | 128,000,000 (2020 US$)[a] | Shirvan (2022) |
| HTGR | 281 | 60,000,000 (2009 US$) | Gandrik et al. (2012) |
| SFR | 1200 | 219,000,000 (1996 US$)[b] | Schneider (2009) |

[a] The reference year was not specified, so we generally assumed it as 2020 US $. All annual O&M cost figures were rounded to the nearest million US$ for simplicity and clarity. This is because the provided figure for the AP1000, for instance, was listed as 128 million, and we applied rounding for consistency across all reactor types.

[b] The operating costs of Superphénix were reported as FRF 1.7 billion per year. Since O&M costs comprise about 66 % of the total operating costs (World Nuclear Association, 2023b), we multiplied 1.7 billion FRF by 0.66, converting the result to US$.

scenarios, and precise calculations remain elusive.

### 2.3. O&M costs

#### 2.3.1. O&M cost calculation using the economy of scale

The O&M costs of nuclear are an important factor to account for when calculating the LCOE (Carelli et al., 2008). O&M costs of a nuclear power plant are based on the required personnel and the materials during facility operation (National Academies of Sciences Engineering and Medicine, 2023a). However, realistic estimates of these O&M costs are challenging due to the absence of operational or demonstration SMRs in the U.S. In a recent study, fixed O&M cost estimates depended on data from academic sources, not actual experience (Steigerwald et al., 2023). For concepts like SFRs, which lack available O&M cost data, Steigerwald et al. (2023) used the average ($130.75/kWe-yr) of Lazard's (2021) nuclear fixed O&M cost range ($121.00-$140.50/kWe-yr) for estimating O&M costs. However, these computations have limitations as they either stem from academic sources or display significant dispersion within the same reactor type, with PWRs exhibiting higher O&M costs than SFRs. Other research estimated the general SMR fixed O&M costs at AU$200/kWe-yr (equivalent to US$134/kWe-yr[6]) and the variable O&M costs at AU $5.3/MWh (equivalent to US$3.55/MWh) (Graham et al., 2023).

Yet, some studies have demonstrated that economies of scale will play a significant role in determining higher O&M costs for SMRs compared to large LWRs (Lewis et al., 2016; Mignacca and Locatelli, 2020; Ramana, 2021; Ramana and Ahmad, 2016). This is because personnel costs constitute approximately 50 % of fixed O&M costs (Lewis et al., 2016), owing to specific fixed personnel requirements and expenses that persist regardless of the amount of electric power generation. For example, some studies calculated or used an economy of scale (n = 0.6–0.71) in the O&M costs or sensitivity analyses (Carelli et al., 2008; Stauff et al., 2021). Although co-siting and operational learning may slightly reduce fixed and variable O&M costs, still SMR O&M costs are generally expected to be higher than those of large LWRs (Lewis et al., 2016).

As such, we solely utilized the economy of scale to calculate O&M costs, based on the O&M cost estimates of reference reactors in previous research/data in this study. For PWR and BWR type reactors, we used O&M cost estimates from the AP1000 for the reference value (Shirvan, 2022). For SFR type reactors, we used the Superphénix annual operating cost (Schneider, 2009) and converted into 2023 US$. For HTGR reactors, actual O&M costs could not be obtained. As such, we utilized the estimated annual O&M costs provided by the Idaho National Laboratory for HTGR type reactors (Gandrik et al., 2012). Rather than separating variable and fixed O&M cost data, we used annual O&M cost estimates (US $/year) from each reference and scaled using the economy of scale factor as 0.7 (see Table 7). The final O&M cost calculation is described in Eqs. (16) and (17).

$$O\&M_{SMR,types,MWe}\left[\frac{\$}{\mathrm{MWe}}\right] = O\&M_{Reference,types,MWe}\left(\frac{P_{SMR,types,MWe}}{P_{Reference,types,MWe}}\right)^{n-1} \quad (16)$$

$$Annual\ O\&M\ cost\left[\frac{\$}{MWh}\right] = \frac{O\&M_{SMR,types,MWe}}{365 \times 24 \times C_f} \quad (17)$$

#### 2.3.2. Discussion of the uncertainties in O&M costs

The estimated value encompasses its own uncertainties, as we derived it by scaling from the O&M estimates of previous studies using the economy of scale. A limitation arises from the inability to precisely calculate the operation personnel required for each SMR, given that they are still in the design stage, and the exact personnel details are yet to be determined.

Manufacturers advocate for characteristics such as cost-saving, automatic, and passive systems, which could potentially reduce O&M costs. For example, NuScale has actively advertised that the flagship VOYGR-12 plant (924 MWe with 12 NuScale Power Modules) is projected to have a workforce of approximately 270 individuals (International Atomic Energy Agency, 2022), with a minimum of 3 licensed operators per shift in the control room (International Atomic Energy Agency, 2022; NuScale, 2023b). Given that we only calculated the O&M costs for one module (77 MWe), VOYGR-12 plant may have decreased O&M costs per module if it is possible to reduce the number of personnel for a plant during actual plant operation. The BWRX-300 reactor plans to reduce costs via natural circulation systems, a smaller containment structure, and passive operational control systems. GE-Hitachi plans to limit onsite workers to 75, resulting in an estimated O&M cost of $16/MWh (Reuters, 2018). TerraPower also suggested that the Natrium reactor will use architectural innovations to reduce O&M costs, and plan to have 65–125 onsite staff (Neider, 2021). However, since these plants have not received a license, these costs savings remain uncertain.

Nonetheless, there are significant challenges in estimating non-LWR O&M costs due to uncertainties in costs for safeguards and physical security at these plants. For those non-LWRs that use HALEU fuel, the material attractiveness of the fuel will be higher than that for LEU fuel (i.e. Frieβ et al., 2015; Glaser et al., 2013; Mulyana and Chirayath, 2023). For example, Natrium reactors may not impose significantly greater additional inspection burdens per unit compared to large LWRs; however, due to the use of HALEU fuel compared to large LWRs, alterations in safeguards procedures and inspection approaches will be needed, potentially leading to higher overall inspection requirements on a per-megawatt basis (National Academies of Sciences Engineering and Medicine, 2023b). Additionally, in the case of pool-type SFRs, the National Academies (2023b) report pointed out that the opacity of sodium and the positioning of fuel may restrict direct visual inspections, posing additional challenges. While TerraPower (Hejzlar, 2021; Neider, 2021) has stated that spent fuel assemblies are "tagged and easily accountable," the National Academies (2023b) report emphasized the lack of clarity regarding methods for verifying these tags, thus indicating the requirement for new approaches. If spent fuel is processed, then certainly there will be additional costs associated with both physical security and safeguards at reactor facilities.

Similarly, material accountancy poses greater challenges for pebble-bed reactors compared to stationary solid fuel systems due to technical difficulties in measurement and bulk-handling facilities. Pebble-bed reactors, characterized by online refueling, will require different safeguards approaches and may demand more resources than batch-refueled

[6] We generally assume AU$1 equals US$0.67.

reactors like large LWRs (National Academies of Sciences Engineering and Medicine, 2023b). In addition, the Xe-100 plans to use HALEU fuel, and as with Natrium, will require enhanced safeguards due to the quantities of Category-II materials that will be onsite (National Academies of Sciences Engineering and Medicine, 2023b).

Since the U.S. is already a nuclear weapons state, there may be less concern about safeguards measures regarding nuclear material accountancy (National Academies of Sciences Engineering and Medicine, 2023b). If SMRs are deployed in countries other than nuclear weapons states, however, this may increase the number of devices and sites requiring detection of the diversion of nuclear material compared to the large LWRs, potentially raising the burden on IAEA inspectors and increasing costs for these plants (National Academies of Sciences Engineering and Medicine, 2023b). This is because some countries interested in SMRs rank low in governance quality and capacity indicators, thus increasing vulnerabilities that may introduce new uncertainties in non-proliferation compliance in the future (Kim and Chirayath, 2024; L'Her et al., 2024). Meanwhile, the National Academies (2023b) report suggests that the U.S. modify and enhance current physical security requirements and relevant legislation tailored to LEU facilities, as part of the preparations for physical protection and cybersecurity to address potential sabotage and nuclear theft by non-state actors. Such modifications have the potential to increase regulatory fees, and of course, may add to overall costs.

At facilities using HALEU fuel and non-water coolants may require larger fixed staffing components, particularly for safeguards and physical security compared to LEU facilities, irrespective of plant capacity. These additional costs would also apply to Category-II enrichment and fuel fabrication facilities. As a result, physical security and safeguards costs are still highly uncertain for non-LWR O&M costs.

Lastly, the standardized design of SMRs could also impact maintenance costs if critical, generic defects are found in a particular design, as illustrated by the recent experience in France. At the end of 2021, serious stress corrosion cracking was initially discovered in the safety injection systems of France's largest and most recently constructed nuclear reactors, Chooz and Civaux (Moyer, 2022; Rudland et al., 2024). In 2022, nuclear power in France accounted for 63 % of the electricity supply, compared with 78 % in 2005. In fact, in August of 2022, almost 65 % of the French nuclear fleet was not operable (Réseau de Transport d'Électricité, 2022). EDF decided to inspect all reactors by the end of 2025 (World Nuclear Association, 2025), with 11 out of 16 reactors identified as most vulnerable to stress corrosion already repaired or preemptively addressed by mid-2023 (as of July 4, 2023) (Électricité de France, 2023). While France has been known for cost savings and increased economic viability through the standardized construction of reactors with identical designs, the discovery of significant flaws in similar or exact-copy models underscores the inevitability of investigations and maintenance for similar reactors, presenting yet another challenge for the standardized modules of SMRs.

### 2.4. Low- and intermediate-waste from different SMR types

After reactors shut down at end of life, the fuel and coolant will be drained, and the structural materials of SMRs will need to be broken down, treated, conditioned, and packaged for final disposal. The U.S. has significant decommissioning and waste management experience with large LWRs. However, costs for SMRs' decommissioning and nuclear waste treatment are uncertain. Accurately estimating decommissioning and waste management costs and including the costs in the LCOE is challenging. Therefore, some studies have neglected the decommissioning and waste disposal costs in the LCOE (Froese et al., 2020; Steigerwald et al., 2023) and another study set decommissioning costs as a specific fraction of the capital cost (i.e., 21.55 % in Asuega et al. (2023)), annualized over the lifetime of the plant with a discount rate. The World Nuclear Association (2023b) suggests that expenses for decommissioning typically range between 9 % and 15 % of the original

**Table 8**
Major nuclear wastes (Class C LLW, GTCC, or other specific level of wastes) from SMRs, based on manufacturers and reports.

| Reactor | Description | Waste level |
|---|---|---|
| BWRX-300 | NA | NA |
| NuScale Power Module | Kim et al. (2022) estimates about 3 m$^3$ from baffle, barrel, and grid plates/Krall et al. (2022), estimates from 2.75 m$^3$ to 5.05 m$^3$ of grid plates, reflector, shroud, barrel and lower pressure vessel | GTCC |
| Xe-100 | By far the largest volume of waste from HTGR is graphite matrix/TRISO fuel from pebbles (National Academies of Sciences Engineering and Medicine, 2023b) | SNF |
| | Kim et al. (2022) estimates about 106 m$^3$ of graphite block | GTCC (if the graphite block resides in the core for all lifetime) |
| | Helium coolant and dust[a] (National Academies of Sciences Engineering and Medicine, 2023b) | LLW or GTCC |
| Natrium | 80 MT of reflector, and reactor-vessel irradiated internals (Hejzlar, 2021; Kim et al., 2022) | Class C or GTCC (if the reflector resides in the core for all lifetime) |
| | 70 MT irradiated control rods (Hejzlar, 2021) | Class C LLW |
| | 4–8 m$^3$ of activated primary cold traps containing tritium and Cs and Cs traps and secondary cold traps containing tritium (Hejzlar, 2021) | GTCC |
| | 800 m$^3$ of sodium coolant (will include sodium-22, tritium, cobalt-60, cesium-137) (Hejzlar, 2021) | LLW |

[a] Helium coolant itself will not undergo radioactivity itself; however, it will get contaminated by radionuclides released from failed/cracked fuel particles and by radioactive carbonaceous dust originating from TRISO (National Academies of Sciences Engineering and Medicine, 2023b).

capital investment in a nuclear power plant for LWRs. It is important to note that, however, there is a high likelihood that the costs associated with handling radioactive waste generated at the power plant and managing various components of the plant during reactor operation vary widely depending on the reactor types.

Although there are several low-level waste (LLW) disposal facilities in the U.S., there is currently no commercially available disposal capacity for Greater-than-Class C (GTCC) LLW in the U.S., making it challenging to calculate the associated disposal costs. GTCC LLW should undergo geological disposal, whereas other LLWs can undergo near-surface disposal. Scholars (Brown et al., 2017; Krall et al., 2022) found that neutron leakage is enhanced in SMRs compared to large LWRs due to the smaller radius and reactor size, resulting in the generation of more long-lived radioisotopes, and therefore higher volume of GTCC. Consequently, the escalation of GTCC volume per unit of energy produced introduces significant uncertainties into the estimation of nuclear decommissioning costs for SMRs.

In this section, we comprehensively examine the characteristics of specific nuclear waste types, including categories A, B, and C low-level waste (LLW), GTCC waste, and other waste volumes that should be treated before final disposal. The details of each nuclear waste type are presented in Table 8. It is important to note that nuclear waste estimates for BWRX-300 were not available for this study.

From our analysis, by far the largest volume of waste from Xe-100 is graphite from reflectors (graphite blocks) and the pebble-based graphite matrix. An Argonne National Laboratory report (Kim et al., 2022) suggested that graphite reflector block of Xe-100 will be around 106 m$^3$ and will be considered GTCC waste if it resides in the core for the entire reactor life. In addition, the majority of graphite waste is from the pebbles. Direct disposal of pebbles (without extracting TRISO coated

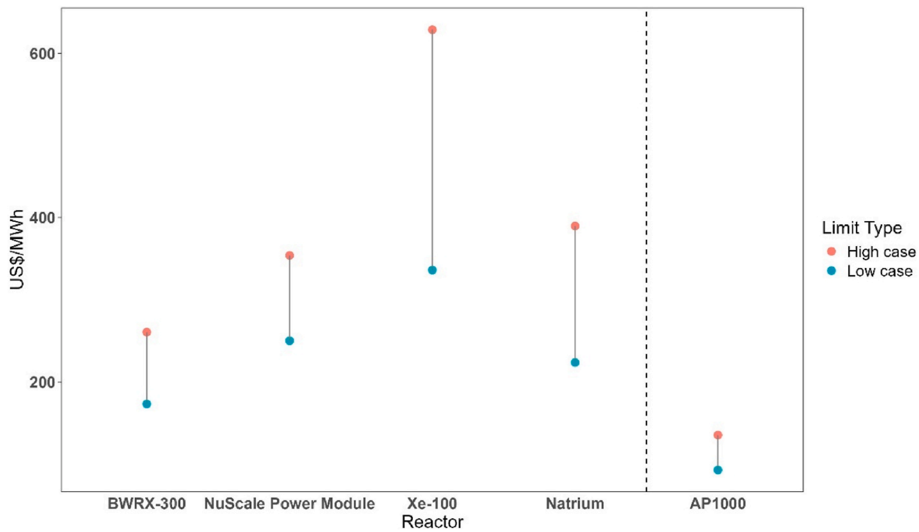


**Fig. 1.** Results of the LCOE calculation (excluding back-end fuel cycle costs and waste disposal/decommissioning costs).

particles from the graphite in the pebbles) as we have discussed in the previous section, will result in large uncertainties in back-end fuel cycle costs. Separating TRISO fuel kernels from the graphite matrix is under development (Grambow et al., 2006; Guittonneau et al., 2010). However, according to the National Academies (2023b) report, this technology remains immature, and it is likely that the graphite waste may contain radionuclides, requiring an additional treatment, which could further increase decommissioning costs. With that said, it is highly likely that extracting the graphite in the pebbles separately from the TRISO particles may not happen due to the increased costs associated with the process.

In the case of Natrium, the vendor suggests that 4–8 $m^3$ of activated primary cold traps will be classified as GTCC, and 80 MT of reflector and reactor-vessel irradiated internals will be classified as Class C LLW (Hejzlar, 2021). However, the Argonne National Laboratory (Kim et al., 2022) indicated that there is a possibility that the reflector will be classified as GTCC if it remains in the core for the entire reactor lifespan.

Moreover, the vendor estimates that approximately 800 $m^3$ of sodium coolant would be generated over the Natrium reactor's lifespan (Hejzlar, 2021). Although the sodium coolant is not considered as GTCC by the vendor, the complexity of radioactive sodium coolants poses a challenge in decontamination and decommissioning, thereby requiring the draining and treatment of all sodium coolant as LLW. Besides activated Na-22, the sodium coolant may contain several radioactive materials, including fission products. Processes for managing the decontamination of this sodium coolant have already been developed according to the International Atomic Energy Agency (2007). However, the National Academies (2023b) report highlighted that a substantial amount of residual sodium will remain in the reactor post-decommissioning, based on past experience. This residual sodium in sodium circuits and unloaded fuel assemblies requires removal due to its reactivity with moisture, posing a significant fire hazard (National Academies of Sciences Engineering and Medicine, 2023b). Therefore, additional work on treating residual sodium could pose additional uncertainties for decommissioning costs.

Our review reveals that, among the SMR types, LWRs are anticipated to exhibit the lowest volume of GTCC waste compared to the non-LWR types, although the exact amount for the BWRX-300 could not be determined based on existing literature. However, a prior study indicated that a light water SMR may still create a higher volume of GTCC waste compared to a large PWR, per unit energy (Krall et al., 2022). Nevertheless, another previous study states that the total waste volume of GTCC in NuScale Power Module is minimal— approximately just 5 % of the total LLW volume (Kim et al., 2022). The cost of conditioning, packaging, and disposal for GTCC waste still remains uncertain, and there is significant uncertainty regarding the amount of LLW generated in non-LWR reactors. In summary, numerous uncertainties persist regarding the decommissioning and waste management/disposal costs of SMRs, especially for non-LWR types.

## 3. Levelized cost of electricity calculation and discussion

As we stated in earlier sections, calculating the exact LCOE of SMRs is significantly challenging due to numerous uncertainties in exact values and a reliance on sources that are not based on empirical data. However, we calculated the LCOE by summing the annualized overnight capital costs, and those for fuel and O&M using the limited data availability. To simplify the calculation of LCOE, we generally used the method proposed by National Renewable Energy Laboratory (Foster et al., 2014), which has been employed similarly in previous studies (Froese et al., 2020; Shirvan, 2022). Since we could not generally project the nuclear waste management/decommissioning costs of each reactor type, we did not include these costs in this calculation.

The annualized overnight capital cost and initial core load cost were derived from Eqs. (18)–(21). We did not consider the tax rate or present value of depreciation in this study for simplicity, although a previous study (Shirvan, 2022) considered these factors when calculating LCOE for the AP1000. We have assumed a 90 % capacity factor for all reactor types. The *CRF* represents capital recovery factor, which turns capital costs into annual values for the reactor lifetime (60 years in all reactor types in our study). With a discount rate ($D$) as 5%, and the time frame during which the cost is amortized ($T_L$) as 60 years, same as the reactor lifetime, our total LCOE values of four different types of FOAK SMRs are shown in Fig. 1. We also calculated the LCOE of AP1000 using the same methods. This approach is to compare a typical large LWR and different SMRs within our study.

$$\text{LCOE}\left[\frac{\$}{MWh}\right] = \textit{Annualized overnight capital cost} + \textit{Annualized initial core load cost} + \textit{Annual refueling cost} + \textit{Annual O\&M cost} \tag{18}$$

$$\textit{Annualized overnight capital cost}\left[\frac{\$}{MWh}\right] = \frac{OCC_{SMR,types,MWe} \times CRF}{365 \times 24 \times C_f} \tag{19}$$

$$\textit{Annualized initial core load cost}\left[\frac{\$}{MWh}\right] = \frac{FC_{SMR,types,initial\ load} \times CRF}{365 \times 24 \times C_f \times P_{SMR,types,MWe}} \tag{20}$$

$$CRF = \frac{D \times (1+D)^{T_L}}{(1+D)^{T_L} - 1} \quad (21)$$

Our results indicate that among different types of SMRs, the non-light water SMRs, Xe-100 and Natrium, exhibit higher LCOE compared to other light water SMR types, with BWRX-300 having the lowest LCOE. For LWRs, the LCOE of NuScale Power Module is still higher than that of BWRX-300, per MWh. Our estimates conclude that Xe-100 has the highest LCOE among all types of SMRs. This is largely attributed to the reference overnight capital cost projection from the THTR-300 reactor. Despite Natrium's larger capacity (345 MWe) compared to NuScale Power Module (77 MWe), its LCOE remains similar, with a higher upper bound in the high case. This may result from its non-LWR characteristics or from low LCOE estimates that do not fully account for all overnight capital costs. Although our analysis does not incorporate temporal weighting of individual cost components across different scenarios, our simplified LCOE results indicate that overnight capital costs account for the largest share of total LCOE, ranging from approximately 66–87 % across SMR types. This implies that reducing overnight capital costs is the most effective pathway to improving economic competitiveness of SMRs.

The front-end fuel cycle cost calculation approach also facilitates comparisons among different SMR types. Our analysis (see Supplementary Materials) indicates that the BWRX-300 exhibits the lowest annual refueling cost compared to other reactor types. The higher cost of the NuScale Power Module compared to the BWRX-300 is, in part, attributed to its lower power generation compared to the BWRX-300, resulting from diseconomies of scale. Both the Xe-100 and Natrium display higher annual refueling fuel cycle cost values than the BWRX-300, primarily due to higher fuel fabrication costs in comparison to those of LWRs. Overall, the fuel costs of SMRs tend to be similar to or even higher than those of AP1000, which is consistent with the findings of Pannier and Skoda (2014) and Shirvan (2022). However, it is important to note that these value comparisons also entail numerous uncertainties, which are discussed above in Section 2.2.2. When considering the back-end fuel cycle/waste management costs, there is a significant possibility that the Xe-100 and Natrium's LCOE will even further surpass those of the BWRX-300 and the NuScale Power Module, owing to its large volume of SNF and/or GTCC waste and non-LWR fuel enrichment/fabrication costs.

Our results again demonstrate that the O&M costs of SMRs are much higher for non-light water SMRs than light water SMRs. According to a Nuclear Energy Institute (2023) report, the estimated operating costs for large nuclear power plants in the U.S. in 2022 are $18.68/MWh in 2022 US$. Meanwhile, our O&M costs for the BWRX-300 are comparable to the reported value of $22/MWh (in 2020 US$) for FOAK SMR O&M costs as stated in the Nuclear Energy Institute (2021) report, even though this estimate is based on a 600 MWe plant (150 MWe × 4 cores). The highest O&M costs in our study are for the SFR and HTGR type reactors. The analysis suggests that Xe-100 O&M costs would be relatively lower than those of Natrium; however, this is because while the Natrium used the actual operating cost of Superphénix, there is no actual O&M estimate available for the cost of HTGR type. The NuScale Power Module ranked as the second-lowest, primarily due to its lower electricity generation compared to the BWRX-300.

It is noteworthy that our LCOE estimates for the AP1000 used for comparison still remain below LCOE figures reported in other studies. For instance, Lazard's recent LCOE projections for nuclear energy in 2023 range from US$141/MWh to US$221/MWh (Lazard Ltd, 2023), and in 2021, the range is from US$131/MWh to US$204/MWh (Lazard Ltd, 2021), surpassing our AP1000 LCOE projections. This discrepancy could stem from variations in LCOE calculation methods. When the input values from Lazard's (2023) 16th version are incorporated into our LCOE calculation, however, the resulting value ranges fall slightly below our projections, as indicated in our Supplementary Materials. Additionally, our calculations did not include back-end fuel cycle costs, decommissioning/waste management costs, safeguards/security costs, carbon tax credits, or considerations for tax depreciation and other tax rates. We do not recommend comparing this study's LCOE values to those of other studies due to differences in LCOE calculation methods and assumptions.

Nevertheless, our results consistently demonstrate that, regardless of SMR type, the LCOE for SMRs is more than twice as high as those of the AP1000. These results once again emphasize the numerous challenges that SMRs face in overcoming economic obstacles, aligning with similar arguments from previous studies (Rothwell, 2015, 2022; Shirvan, 2022; Steigerwald et al., 2023; Thomas and Ramana, 2022).

## 4. Conclusions and policy implications

According to our comprehensive review and analysis of the LCOE of four distinct types of SMRs, our conclusions are as follows:

- It is likely that both overnight capital and O&M costs for SMRs will surpass those of standard large LWRs, due to diseconomies of scale. Consequently, the electricity cost from SMRs is anticipated to exceed that from standard large LWRs.
- Although there are arguments that construction time, modularization, and learning rate will reduce overnight capital costs of SMRs, there remain significant uncertainties in achieving these lower costs when considering historical trends. These trends, specifically in the U.S. and Western countries, suggest that the possibility of learning, modularization, and reducing construction time will not reduce costs significantly; indeed, they can result in an increase in construction costs.
- When calculating the front-end fuel cycle cost, the BWRX-300 was found to be lower compared to the NuScale Power Module. This is attributed to each BWRX-300 plant generating more electricity, suggesting economies of scales are at play.
- Although we could compute the front-end fuel cycle cost of non-light water SMRs, the result would be highly uncertain in value as there are no operational commercial HALEU enrichment facilities outside of Russia, nor any non-LWR fuel fabrication facilities of commercial scale.
- Considering the back-end of the fuel cycle and waste management costs, non-light water SMRs are at high risk for cost increases due to HALEU management, SNF volume/radiotoxicity, GTCC waste treatment, and processing and disposal of non-light water SNF. Specifically, the SNF volume of Xe-100 is much higher than that of other SMR types presented in this study.

Our analysis indicates that due to the uncertain development and commercialization timelines, as well as the diseconomies of scale associated with these SMR designs, this technology is unlikely to significantly impact the reduction of carbon emissions in the foreseeable decades. Moreover, new approaches to nuclear waste management and disposal will be imperative to commercialize non-LWR types. This makes SMRs less directly relevant to current climate change challenges.

Though construction durations and expenses vary across nations, this investigation focused on the U.S. As such, caution must be exercised in extending these evaluations to other global contexts. Our review and cost analyses coalesce to assert that, driven solely by economies of scale, the deployment of SMRs may exacerbate financial risks for both established and newcomer countries.

Therefore, it is of the utmost importance for the nuclear industry to explore innovative approaches aimed at reducing capital cost overruns in large LWRs while ensuring that these efforts do not compromise safety by reducing necessary regulations or eliminating redundant safety features. This strategic shift to reduce the cost overruns of large LWRs while improving safety features could potentially enhance the commercial appeal of nuclear power, particularly for newcomer countries venturing into nuclear energy. Nuclear energy newcomer countries can be more vulnerable to additional costs and extended construction timelines, hindering the progress of adopting nuclear energy further.

Many countries, governments, and utilities are interested in SMRs. In an effort to make informed decisions about these potential energy sources, a robust understanding of all costs is needed. This paper provides a first attempt to consider all costs associated with this technology. We hope to spark further analyses with this study.

## CRediT authorship contribution statement

**Philseo Kim:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Allison Macfarlane:** Writing – review & editing, Supervision, Investigation, Funding acquisition, Formal analysis, 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.

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## Appendix

**Table A 1**
Original overnight capital cost estimates of reference reactors

| Reference reactor | Original overnight capital cost estimates | References |
|---|---|---|
| ESBWR (GE-Hitachi) | 8,593/kWe (in 2015 US$) | Schlissel (2016) |
| Vogtle-3 | 8,600/kWe (in 2018 US$) | (IEA, 2025; Rothwell, 2022) |
| | 14,700/kWe (in 2023 US$) | |
| THTR-300 | 17,000/kWe (in 2008 US$) | Dixon et al. (2017) |
| Superphénix | 8,870/kWe (in 2006 US$) | Dixon et al. (2017) |

**Table A 2**
Inflation adjustment factors to 2023 US$

| Year | Factor |
|---|---|
| 1996 | 1.94 |
| 1997 | 1.9 |
| 1998 | 1.87 |
| 1999 | 1.83 |
| 2000 | 1.77 |
| 2001 | 1.72 |
| 2002 | 1.69 |
| 2003 | 1.66 |
| 2004 | 1.61 |
| 2005 | 1.56 |
| 2006 | 1.51 |
| 2007 | 1.47 |
| 2008 | 1.42 |
| 2009 | 1.42 |
| 2010 | 1.4 |
| 2011 | 1.35 |
| 2012 | 1.33 |
| 2013 | 1.31 |
| 2014 | 1.29 |
| 2015 | 1.29 |
| 2016 | 1.27 |
| 2017 | 1.24 |
| 2018 | 1.21 |
| 2019 | 1.19 |
| 2020 | 1.18 |
| 2021 | 1.12 |
| 2022 | 1.04 |
| 2023 | 1 |

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pnucene.2025.105989.

## Data availability

We have shared data using supplementary materials.

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