COST PROJECTIONS OF SMALL MODULAR REACTORS: *A Model-Based Analysis*

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Abstract

Forecasting the future costs of innovative energy technologies, such as small modular reactors (SMRs), presents a complex challenge due to a multitude of uncertainties and variables. This paper presents a model-based approach for estimating the cost and learning curves of SMRs. The analysis reveals that while smaller SMRs may initially face higher costs, they possess significant potential for cost reduction, driven by reduced construction time and learning effects. Further, the study shows that SMRs can competitively match or surpass the cost-efficiency of larger nuclear power plants, conditional on the deployment of a sufficient number of units. Finally, future cost projections are presented, with and without the inclusion of heat use and with and without the long-term economics of SMRs, providing a nuanced perspective of their economic value.

1. INTRODUCTION

Nuclear energy has historically leveraged economies of scale to obtain cost competitiveness. Even though the first reactors were small, the nuclear industry gained experience, and the reactors got bigger, not smaller. However, the construction experience seems to have evaporated in the Western world, and recent megaprojects have led to cost/schedule overruns, resulting in a growing doubt that Western countries are able to execute giant nuclear projects. Eash-Gates et al. (2020) performed a bottom-up cost modeling approach to quantify the source of the cost overruns [1]. They found that the costs of containment buildings doubled from 1976 to 2017 and that labor productivity was 13 times lower than industry expectations. Stewart and Shirvan (2023) found that change orders contribute to most construction delays, while supply chains have had the least impact, emphasizing the need to complete the detailed design before construction [2]. To deal with some of the project and financial risks of nuclear power plants (NPPs), small modular reactors (SMRs) have been proposed to increase the likelihood of delivering on the expected time and budget. However, as the smaller reactors inherently lack economies of scale benefits, they must be overcome by higher learning rates driven by the economics of mass production [3, 4].

Idaho National Laboratory (INL) projects a high-case scenario for SMRs with a learning rate 15 % per cumulative doubling of units [5]. In such an optimistic scenario, the deployment of 32 SMR units will lead to an overnight construction cost (OCC) reduction of 55.6 %. Similarly, energy analytics firm Wood Mackenzie expects levelized cost of electricity (LCOE) of around \$180/MWh for first-of-a-kind (FOAK) SMRs but that the LCOE will reduce by 40% to \$100/MWh by 2030, mainly driven by innovation and scaling up [6]. Nevertheless, the future cost prospects of SMRs have recently been debated in the literature, where Nøland and Hjelmeland (2024) [7] have recently argued that the cost model assumptions of Steigerwald et al. (2023) [8] are inaccurate.

There is a scarcity of available cost information on nuclear, and especially for SMRs. To support capacity expansion planning toward a decarbonized power system, this paper presents a model-based analysis to evaluate the role of SMRs. Future cost projections of SMRs are provided, including the value of both heat and power, and the impact of long-term operation. The rest of the paper is organized as follows. Section 2 presents some basic economic modelling of SMRs before Section 3 presents the main analysis, and Section 4 concludes the paper.

2. ECONOMIC MODELING

2.1. Economics of scale

Economics of scale has historically been the major contributor to cost reductions in nuclear energy economics. According to eq. (1), the overnight construction cost (c), or the OCC, of a nuclear power plant (NPP) relative to its baseline cost (c_b) is determined by the ratio between its power rating (P) and the baseline power rating (P_b) and the scaling coefficient (k) originating from production theory [3, 6]. If coefficient $k = 1$, the OCC becomes independent of power rating, and the economics of scale effect vanishes.

$$\frac{c}{c_b} = \left(\frac{P}{P_b}\right)^{k-1} \tag{1}$$

Table 1 lists typical values and ranges of values found in the literature. Some power components can have even lower scaling coefficients, but when considering the overall scaling effect of the NPP, representative ranges of values are in the range between 0.7 and 0.4, with 0.6 as the rule-of-thumb [8].

TABLE 1. SCALING COEFFICIENTS REPORTED IN THE LITERATURE.

Source	Lower value	Medium value	Upper value	Reference
Rasmussen *et al.* (1996)	–	0.60	–	[9]
Carelli *et al.* (2010)	0.50	0.60	0.70	[10]
NEA/OECD (2000)	0.40	0.55	0.70	[11]
Moore (2016)	–	0.55	–	[12]
Rothwell (2016)	–	0.85	–	[13]

The OCC of an SMR is sensitive to the economics of scale effect, which is highlighted in Table 2 based on eq. (1). For a general 300-MW SMR, the costs increase by 13 % to 83 %, depending on the scaling coefficient. This cost increase would need to be compensated by other economic advantages to make SMRs competitive with large reactors.

TABLE 2. OVERNIGHT CONSTRUCTION COST OF SMALL MODULAR REACTORS WITH DIFFERENT RATINGS AND SCALING COEFFICIENTS VS. LARGE NUCLEAR REACTORS (1000 MW)

Power rating	Scaling coefficient					
	k = 0.5	k = 0.6	k = 0.7	k = 0.8	k = 0.9	k = 1.0
100 MW	316 %	251 %	200 %	158 %	126 %	100 %
200 MW	224 %	190 %	162 %	138 %	117 %	100 %
300 MW	183 %	162 %	144 %	127 %	113 %	100 %
400 MW	158 %	144 %	132 %	120 %	110 %	100 %
500 MW	141 %	132 %	123 %	115 %	107 %	100 %

2.2. Economics of mass production

One important economic opportunity of SMRs over large reactors is the potential for economies of mass production. Eq. (2) estimates the overnight construction cost normalized with the baseline cost (c_b) as a function of number of units (n) deployed and with an endogenous learning rate (x).

$$\frac{c}{c_b} = n^{\frac{\ln(1-x)}{\ln 2}} \tag{2}$$

Eq. (3) reformulates eq. (2) with respect to the cumulative installed capacity ($\sum P$) scaled with the power capacity per unit (P).

$$\frac{c}{c_b} = \left(\frac{\sum P}{P}\right)^{\frac{\ln(1-x)}{\ln 2}} \tag{3}$$

As highlighted in Table 3, potential learning rates for SMRs vary considerably. In general, pessimistic learning is roughly 5 %, while the more optimistic rate is 15%. The key to achieving high learning is standardized design with little or no variations between units.

TABLE 3. LEARNING RATES REPORTED IN THE LITERATURE.

Source	Study method	Low learning	High learning	Reference
Clack *et al.* (2022)	Top down	–	5 %	[14]
Rubio and Tricot (2016)	Bottom up	5 %	10 %	[15]
Roulstone *et al.* (2020)	Bottom up	2 %	15 %	[16]
Nichol and Desai (2019)	Top down	5 %	15 %	[17]
Abou-Jaoude *et al.* (2023)	Top down	5 %	15 %	[18]
Stewart and Shirvan (2022)	Bottom up	3 %	16 %	[19]

To understand the potential cost reductions of SMRs, Table 4 provides normalized estimates of the overnight cost as a function of the number of deployed units. In the most optimistic case of a 15 % learning rate, the deployment of 64 SMRs will lead to cost reductions of nearly one-third.

TABLE 4. NORMALIZED OVERNIGHT CONSTRUCTION COSTS (OCC) AS A FUNCTION OF NUMBER OF UNITS DEPLOYED FOR DIFFERENT ENDOGENOUS LEARNING RATE SCENARIOS

Scenario	Learning	Number of units deployed						
		n = 1	n = 2	n = 4	n = 8	n = 16	n = 32	n = 64
Pessimistic	x = 5 %	100.00 %	95.00 %	90.25 %	85.74 %	81.45 %	77.38 %	73.51 %
Moderate	x = 10 %	100.00 %	90.00 %	81.00 %	72.90 %	65.61 %	59.05 %	53.14 %
Optimistic	x = 15 %	100.00 %	85.00 %	72.25 %	61.41 %	52.20 %	44.37 %	37.72 %

2.3. Combined economic effects

All economic effects should be combined to evaluate the competitiveness of SMRs with respect to large reactors. To understand scale and mass production economics, Fig. 1–(a) plots the increased cost of an SMR due to lack of economics of scale, and Fig. 1–(b) plots the reduction of cost due to learning.

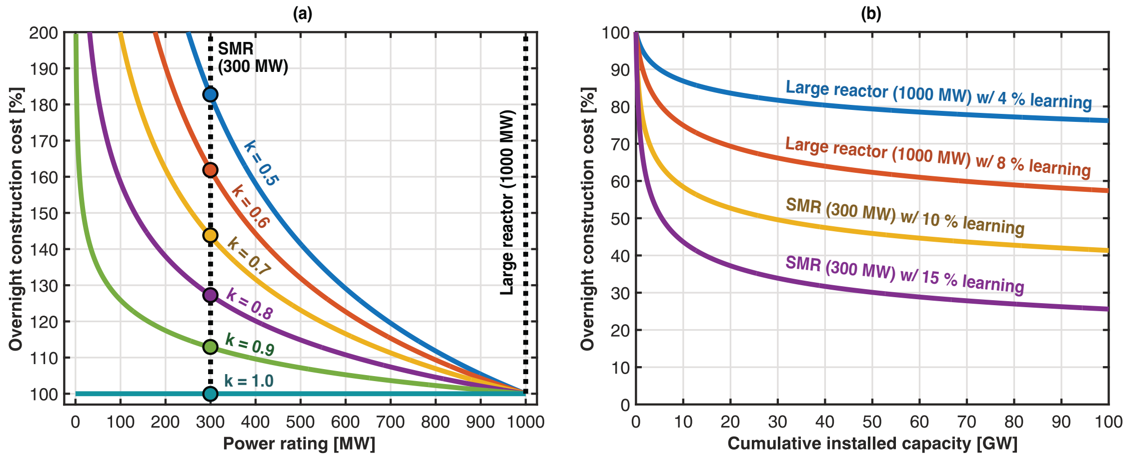

FIG. 1. ***(a)*** *OCC as a function of downscaling a baseline reactor using eq. (1).* ***(b)*** *OCC as a function of the deployed cumulative electrical capacity for both SMRs and large reactors with different endogenous learning rates using eq. (3).*

The cost reductions shown in Fig. 1–(b) highlights that the steep learning effect quickly flattens out as the cumulative deployed SMR capacity increases. The higher achieved cost reductions of SMRs must be higher than the higher initial costs of SMRs shown in Fig. 1–(a) to make them competitive. The question is, what does it take to compensate for the cost increase of SMRs with the cost reductions due to learning? This is shown in Table 5, where a rule-of-thumb scaling coefficient of 0.6 implies that eight units are needed with a learning rate of 15 %.

TABLE 5. NUMBER OF UNITS NEEDED TO COMPENSATE FOR THE LACK OF ECONOMICS OF SCALE IN SMALL MODULAR REACTORS (300 MW) VS. LARGE NUCLEAR REACTORS (1000 MW)

Scenario	Learning	Scaling coefficient					
		k = 0.5	k = 0.6	k = 0.7	k = 0.8	k = 0.9	k = 1.0
Pessimistic	x = 5 %	3412	671	132	26	6	1
Moderate	x = 10 %	53	24	11	5	3	1
Optimistic	x = 15 %	14	8	5	3	2	1

3. FUTURE COST PROJECTIONS

A thorough statistical analysis of SMRs and large reactors in the US has been conducted by the Idaho National Laboratory [19], as listed in Table 6. The OCC is provided in different quartiles, and SMRs will be more expensive in 2030 but will be more competitive in 2050.

TABLE 6. OVERNIGHT CONSTRUCTION COST (OCC) RANGE AND PROJECTIONS FOR SMALL MODULAR REACTORS AND LARGE NUCLEAR REACTORS CONVERTED TO 2024 DOLLAR [19]

Quartile	Coverage	Small modular reactor 300 MW			Large nuclear reactor 1000 MW		
		2030	2040	2050	2030	2040	2050
Upper	75 %	\$10,710/kW	\$8,568/kW	\$6,694/kW	\$8,300/kW	\$8,033/kW	\$6,426/kW
Median	50 %	\$8,568/kW	\$5,623/kW	\$4,284/kW	\$6,158/kW	\$5,087/kW	\$4,016/kW
Lower	25 %	\$5,891/kW	\$2,678/kW	\$2,142/kW	\$5,623/kW	\$3,213/kW	\$2,410/kW

3.1. Total capital cost

To evaluate the overall economics of SMRs, the construction time must be considered. Eq. (4) describes the cumulative capital expenditure, $f(t)$, during the construction time (T), assuming a sinusoidal spending curve [19]. Differentiation of this eq. (4) yields the capital use distribution, $f'(t)$, throughout the construction period, as expressed in eq. (5). The sine wave implies that most capital is used in the middle of the period, as seen in Fig. 2.

$$f(t) = \frac{c}{2} - \frac{c}{2}\cos\left(\pi \cdot \frac{t}{T}\right) \quad (4)$$

$$f'(t) = \frac{\pi}{T} \cdot \frac{c}{2}\sin\left(\pi \cdot \frac{t}{T}\right) \quad (5)$$

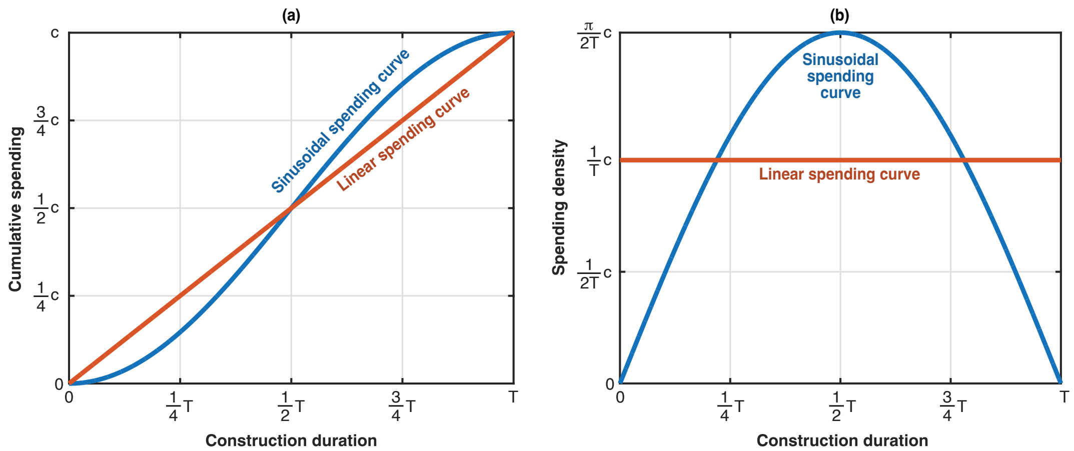

FIG. 2. Generic comparison of sinusoidal and linear spending curves during nuclear reactor construction [18]. ***(a)*** *Cumulative spending according to eq. (4).* ***(b)*** *Spending density according to eq. (5).*

Eq. (6) integrates $f'(t)$while incorporating the weighted average cost of capital (r) to estimate the total capital costs (c_{tot}) as a function of the OCC (c) and the construction time (T). Some parameters to be used in the estimation are provided in Table 7.

$$c_{tot} = \int_0^T (1+r)^{(T-t)} \cdot f'(t) \cdot dt = \frac{c}{2} \cdot \frac{1+(1+r)^T}{1+\left(\frac{T}{\pi}\right)^2 \ln^2(1+r)} \quad (6)$$

TABLE 7. CONSTRUCTION TIME AND TOTAL O&M COST IN 2024 DOLLARS FOR SMALL MODULAR REACTORS AND LARGE NUCLEAR REACTORS [19, 20]

Parameter	Symbol	Small modular reactor 300 MW			Large nuclear reactor 1000 MW		
		Lower 25 %	Median 50 %	Upper 75 %	Lower 25 %	Median 50 %	Upper 75 %
Construction time	T	3.58 yr	4.58 yr	5.92 yr	5.00 yr	6.83 yr	10.42 yr
Total O&M cost	d	$28/MWh	$32/MWh	$44/MWh	$28/MWh	$37/MWh	$43/MWh
Lifetime ext.	c_{lto}	n/a	n/a	n/a	$545/kW	$848/kW	$1150/kW

3.2. Levelized cost of electricity

When the total capital cost is established, the levelized cost of electricity (LCOE) can be estimated based on eq. (7), which averages out the net present value (NPV) of the electricity produced with a capacity factor, k, over, t, hours per year. In eq. (7), a 60-year lifetime is assumed, and two 20-year lifetime extensions are included.

$$\text{LCOE} = d + \frac{c_{tot} + \frac{c_{lto}}{(1+r)^{60}} + \frac{c_{lto}}{(1+r)^{80}}}{\sum_{i=0}^{99} \frac{kt}{(1+r)^i}} \quad (7)$$

The OCCs in Table 6 and the cost parameters in Table 7, both based on the INL analysis, are incorporated using eq. (7) to present LCOE estimates of SMRs and large reactors in Table 8. SMR's lower construction times will make them more economically competitive in both 2040 and 2050, while large reactors will have an edge in 2030. However, SMRs are targeted to have lower financial risk, which might lead to a lower WACC, which could make them more competitive already in 2030 when comparing the LCOE. Table 8 assumes a uniform 5 % WACC.

TABLE 8. LCOE RANGE AND PROJECTIONS FOR SMALL MODULAR REACTORS AND LARGE NUCLEAR REACTORS CONVERTED TO 2024 DOLLAR [19] ASSUMING A 5 % INTEREST RATE

Quartile	Coverage	Small modular reactor 300 MW			Large nuclear reactor 1000 MW		
		2030	2040	2050	2030	2040	2050
Upper	75 %	$116/MWh	$101/MWh	$89/MWh	$107/MWh	$104/MWh	$92/MWh
Median	50 %	$88/MWh	$69/MWh	$60/MWh	$80/MWh	$73/MWh	$65/MWh
Lower	25 %	$66/MWh	$45/MWh	$42/MWh	$66/MWh	$50/MWh	$45/MWh

3.3. Levelized cost of energy

Eq. (7) usually only accounts for the cost of electricity generation and overlooks the overall cost of energy if both heat and power are utilized simultaneously. Bertoni *et al.* (2024) show that SMRs can be used for direct air carbon capture (DACC) applications to significantly increase their usable energy from 32 % to up to 85 % by combining heat and power [21]. Eq. (8) corrects eq. (7) by taking this enhanced energy utilization into account. The levelized cost of energy (LCOE*) is reduced with respect to the levelized cost of electricity (LCOE) by the ratio between the electrical efficiency (η_{el}) when only producing power, while the total efficiency (η_{tot}) when both heat and power are delivered. It is worth noting that the electrical efficiency is maximized when producing electrical power only and the energy efficiency is maximized when both power and heat are utilized.

$$\text{LCOE}^{*} = \frac{\eta_{el}}{\eta_{th}+\eta_{el}}\text{LCOE} = \frac{\eta_{el}}{\eta_{tot}}\text{LCOE} \tag{8}$$

Eq. (8) assumes equal economic value of both electricity and heat. Fig. 3 plots eq. (8), assuming a baseline electrical efficiency of 33 %. If 80 % of the energy can be utilized, the overall cost is reduced by nearly 60 %.

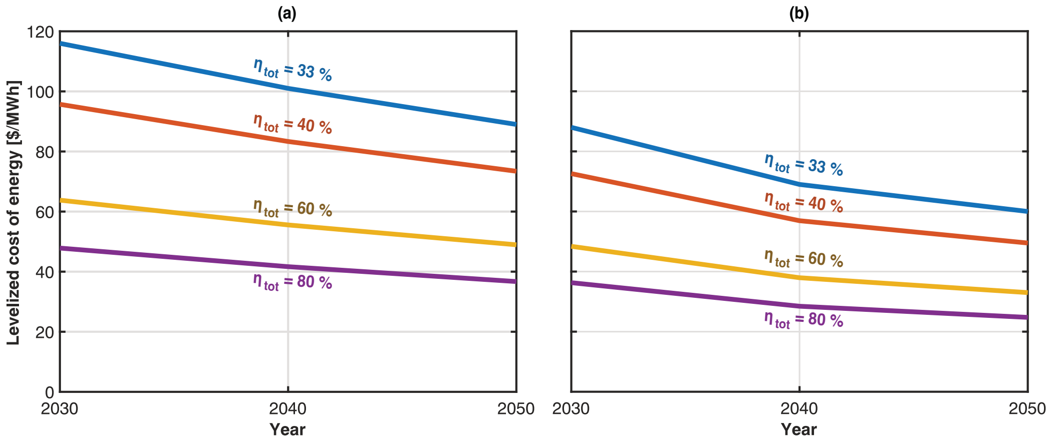

FIG. 3. Levelized cost of energy for SMRs as a function of time and energy utilization by extrapolating baseline values in Table 8 using eq. (8) and assuming 33 % baseline efficiency. ***(a)*** *Upper cost scenario.* ***(b)*** *Median cost scenario.*

3.4. Long-term cost of electricity

There have been concerns regarding how well the LCOE metric captures the long-term value of generation technologies with long lifetimes, such as nuclear energy. To address this concern, we propose the long-term cost of electricity (LTCOE) metric in eq. (9), assuming short capital recovery periods for every investment made over a 100-year horizon. Debt and equity payback times are equal, and no discounting occurs after payback periods.

$$\text{LTCOE} = d + \frac{N}{100}\cdot\left(\frac{c_{tot}}{\sum_{i=0}^{N-1}\frac{kt}{(1+r)^{i}}} + \frac{2\,c_{lto}}{\sum_{i=0}^{N-1}\frac{kt}{(1+r)^{i}}}\right) \tag{9}$$

Fig. 4 shows compare the LCOE and the LTCOE for 15-year and 20-year capital recovery periods (N) with SMRs in 2030 based on Tables 6 and 7, assuming median SMR OCC and construction time, and median lifetime extension cost (based on existing reactors) [20]. The $53/MWh LTCOE shown in Fig4–(b) is significantly lower than the 100-year $88/MWh LCOE, highlighting the benefits of long lifetimes and shorter capital recovery.

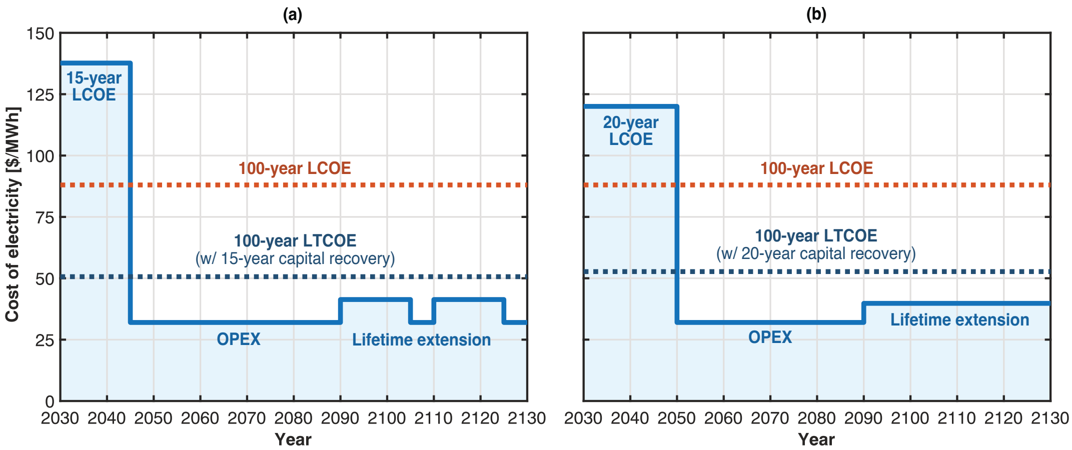

FIG. 4. Comparison of LCOE and LTCOE cost of electricity methods for SMRs over a 100-year time horizon in the median cost scenario in 2030, including long-term operation. ***(a)*** *15-year payback time.* ***(b)*** *20-year payback time.*

4. CONCLUSION

This paper has presented the key economic drivers in the deployment of SMRs, where different assumptions in the cost analysis of SMRs have significant economic effects. The scaling coefficient and the expected learning rate are the most important parameters. Nevertheless, the initially steep learning effect tends to flatten out after the deployment of 10 GW to 20 GW of installed SMR capacity. However, it is still significant enough to make sure its lack of economics of scale can be compensated. Other economic drivers for SMRs are shorter construction times and lower financial risk, which also tend to favor them in the economic analysis. Finally, the utilization of heat can reduce the levelized cost of energy by up to 60 %. Additionally, over a 100-year time horizon with lifetime extensions, the long-term electricity cost could be 40 % lower than the LCOE.

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