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Program on Technology Innovation: A Comparison of Capital Costs Between Large Light Water Reactors and Small Modular Reactors

Considering the Impact of Financing Costs

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ABSTRACT

Capital costs for new nuclear plants are composed of overnight costs and financing costs. Overnight costs include engineering, procurement, and construction and owner's costs. Financing costs are a function of the cost of capital as well as the duration of the project.

Traditionally, many conventional large light water reactor (LWR) projects have incurred significant financing costs because of the risks of large-project execution, licensing, and public acceptance and their effects on project duration and the cost of capital.

Today, a number of light water small modular reactor (SMR) designs from various nuclear developers are on the market. While capital costs on a dollar per kilowatt basis may likely be higher for smaller units due to the loss of economies of scale, there may be advantages gained in financing costs because of the potential for shorter project durations and lower interest rates. This could lead to lower overall total project costs when both overnight and financing costs are considered for smaller reactors as opposed to larger reactors.

This report explores this potential by performing financial modeling and Monte Carlo simulations of first of a kind and nth of a kind conventional LWRs and SMRs.

Keywords

Capital costs
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EXECUTIVE SUMMARY

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Primary Audience: Potential nuclear energy facility owner-operators

Secondary Audience: Nuclear developers, reactor vendors, architect-engineering firms, constructors, public utility commissions, projects financiers/investors, and other stakeholders

KEY RESEARCH QUESTION

There are two key drivers of capital costs for a new nuclear project: overnight costs and financing costs. Traditional large (gigawatt-scale) light water reactors (LWRs) typically have lower overnight costs than proposed light water small modular reactors (SMRs) due to economies of scale. However, SMRs may have lower financing costs because of reduced project risk and construction duration. This research is focused on the question of whether there is a difference in financing costs between the two technologies and if it can affect the outcome of total capital costs.

RESEARCH OVERVIEW

A literature review was conducted on engineering, procurement, and construction (EPC) costs, owner's costs, and financing costs, as well as construction duration and its relationship with EPC costs, for large LWRs and SMRs. Additionally, research was conducted on project risks, factors affecting cost of capital, and financing mechanisms to reduce capital costs for different nuclear power plant designs.

Using data obtained from the literature review, a deterministic financial model was created to analyze financing costs for various cases. Monte Carlo simulations were run for first of a kind (FOAK) and nth of a kind (NOAK) conventional LWRs and SMRs. Comparisons were made between the distribution of capital costs across simulations for the different plant types, and drivers of the differences were analyzed.

KEY FINDINGS

- Across 1000 Monte Carlo simulations, a FOAK SMR has an overall average capital cost that is 16% less than a conventional LWR, primarily driven by lower financing costs resulting from shorter construction durations.

- Across 1000 Monte Carlo simulations, a NOAK SMR has an overall average capital cost that is 5% less than a conventional large LWR, but the probability distributions for capital costs are comparable, implying a similar risk profile for the NOAK projects.
- SMRs provide a hedge against overnight costs as a FOAK SMR can have an 11% premium in overnight costs and still be competitive overall with a conventional FOAK LWR.

WHY THIS MATTERS

When making decisions between different classes of nuclear technology with different overnight costs, construction durations, and costs of capital, total capital costs (including both overnight and financing costs) should be used as input to the decision as opposed to just overnight costs alone.

Utilizing a probabilistic approach can provide additional insights with regard to schedule and cost risk for input into decisions on deploying capital for new nuclear plant projects.

HOW TO APPLY RESULTS

Potential nuclear energy facility owner-operators should evaluate total capital costs, including both overnight and financing costs, when evaluating different sizes of nuclear power plants and making investment decisions.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- EPRI maintains public- and member-facing advisory groups under the Advanced Nuclear Technology (ANT) program that focus on advanced reactor R&D, demonstration, and commercialization topics. These forums provide opportunities for exchanging information and obtaining input on the direction and nature of EPRI's ANT programmatic focus to support deployment of advanced reactors.
- EPRI continues to look for and welcome collaborative opportunities for the development and application of tools and methods that support commercialization of advanced nuclear technology.

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ACRONYMS

ANT	Advanced Nuclear Technology
CAPM	Capital asset pricing model
COD	Commercial operation date
DOE	Department of Energy
EPAct	Energy Policy Act (2005)
EPC	Engineering, procurement, and construction
FFB	Federal Financing Bank
FOAK	First of a kind
IDC	Interest during construction
LWR	Light water reactor
NOAK	Nth of a kind
NPP	Nuclear power plant
SMR	Small modular reactor
UAE	United Arab Emirates

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

Today, there is growing interest in new nuclear power plant (NPP) projects. At the same time, there is a large variety of reactor designs available on the market. These include conventional large light water reactors (LWRs) and light water small modular reactors (SMRs).[1]

Conventional LWRs have increased in size over time to take advantage of economies of scale to lower capital costs on a dollar per kilowatt ($/KWe) basis. However, the increases in size have also shown to have a greater potential for cost overruns and project delays. An Organization for Economic Cooperation and Development summary of recent projects highlights construction delays of 2x and cost overruns of 1.3–4.6x [1]. The rising capital costs for these projects make up at least 60% of their levelized cost of electricity, making them less competitive relative to alternative resources [2]. A significant driver of increased capital costs is financing costs, which can balloon from 10% for an on-time and on-budget NPP to over 30% of capital costs for a delayed and over-budget project.

SMRs present a potential alternative to conventional large LWRs. Although not yet commercially proven, SMRs promise shorter construction durations and a more attractive risk profile that could lead to significant decreases in financing costs, which could result in overall lower capital costs relative to a conventional LWR.

Many potential nuclear plant owner-operators are considering whether to build LWRs or SMRs. Industry convention is to compare different NPPs using overnight costs quoted in a single baseline year, typically at start of construction or at commercial operation date (COD) [3]. This practice omits financing costs, which are particularly relevant when comparing conventional reactors and SMRs with differing construction durations and risk profiles. This report evaluates the role of financing costs in evaluating different sizes of NPPs.

[1] While the term *small modular reactor* or *SMR* can apply to any reactor technology, the use of SMR in this report refers to light water reactor technologies only.

2 OVERVIEW OF NPP CAPITAL COSTS

Overview

Figure 2-1 shows the complete breakdown of NPP capital costs. These costs are described in further detail in this section. It should be noted that while engineering, procurement, and construction (EPC) costs are shown under a single box, that does not imply that an EPC contracting model is used.

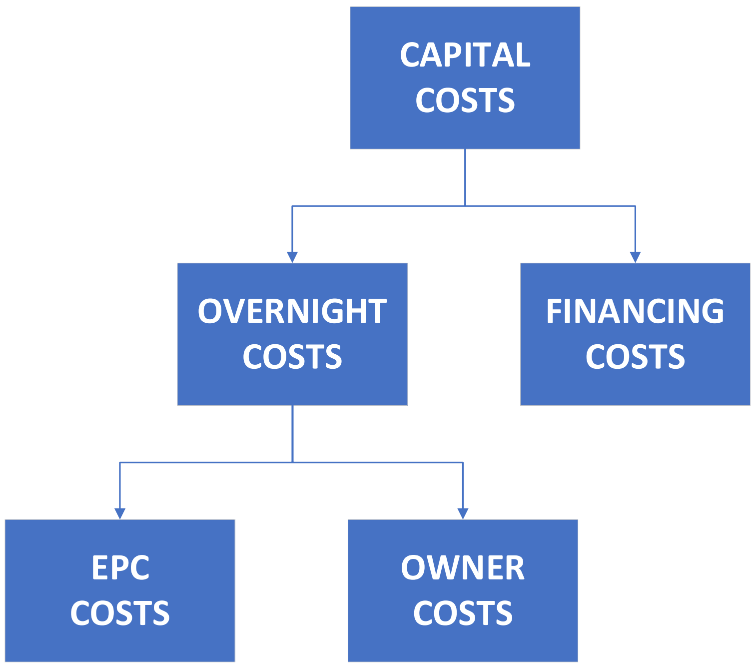

Figure 2-1. Components of capital costs of NPPs

Capital Cost Components

Capital costs of NPPs are typically split into two categories: overnight costs and financing cost (Equation 2-1) [4].

$$\text{Capital Costs} = \text{Overnight Costs} + \text{Financing Cost} \quad \text{Eq. 2-1}$$

Overnight costs consist of all costs borne by the project owner exclusive of financing cost and are represented as if the full cost of the project were incurred "overnight."

Financing cost is the cost of interest for funds (combined debt and equity) used to finance an NPP during construction.

Overnight Cost Components

Overnight cost is often further broken down into EPC cost and owner's cost (Equation 2-2).

Overnight Cost = EPC Cost + Owner's Cost Eq. 2-2

EPC cost is the sum of all engineering costs, procurement costs (equipment, material, and subcontracted services), construction costs, and commissioning costs. EPC costs are typically approximately 80% of the overnight cost.

Owner's cost covers the remaining 20% or so of overnight cost and includes costs that the owner must cover outside the EPC contract, such as preconstruction costs, land, associated buildings and infrastructure, switchyard, grid interconnection, project management, and licensing/permitting [5].

Financing Cost Components

Financing cost, also known as interest during construction (IDC), is compounded and accumulated during construction as the project is not yet generating revenue.

Equation 2-3 captures the components of financing cost where n is a given year of construction up to COD and r_{eff} is the cost of capital.[2] The cost of capital is shown in Equation 2-4.

$$Financing\ Cost = \sum_{n=0}^{n=COD} Overnight\ Cost_n \left(1 + r_{eff}\right)^{COD-n} \qquad \text{Eq. 2-3}$$

$$Cost\ of\ Capital\ (r_{eff}) = Cost\ of\ Debt \times \frac{Debt}{Debt+Equity} + Return\ on\ Equity \times \frac{Equity}{Debt+Equity} \qquad \text{Eq. 2-4}$$

[2] This definition of *cost of capital* is not to be confused with the weighted average cost of capital, which takes into account the tax benefits of using debt over equity. This definition is used to simplify the analysis performed in this study by eliminating the tax treatment of the cost of debt.

3 EFFECT OF CONSTRUCTION DURATION ON NPP CAPITAL COSTS

The average construction time for NPPs between 1976 and 2009 is reported to be 7.7 years [6]. However, several projects have experienced significantly longer construction timelines, including several recent projects [1].

With a significant deviation in past construction durations, it is essential to explore how construction duration affects capital costs.

Construction duration is defined as the time period starting at the first pouring of safety-related concrete and finishing at COD.

Construction Duration Versus Financing Cost

Figure 3-1 shows the effect of construction duration on financing cost for a generic conventional large LWR with an overnight cost of $5,050 and a cost of capital of 6.3%. At a construction duration of 4 years, financing cost accounts for 11% of capital cost, but at 10 years this figure increases to 30%. In this example, overnight cost is fixed and uniformly distributed across each year of construction. However, as construction duration increases, IDC is accrued and compounded over a longer period, resulting in higher financing costs. An example from a recent project shows financing costs at 20% of capital costs [7].

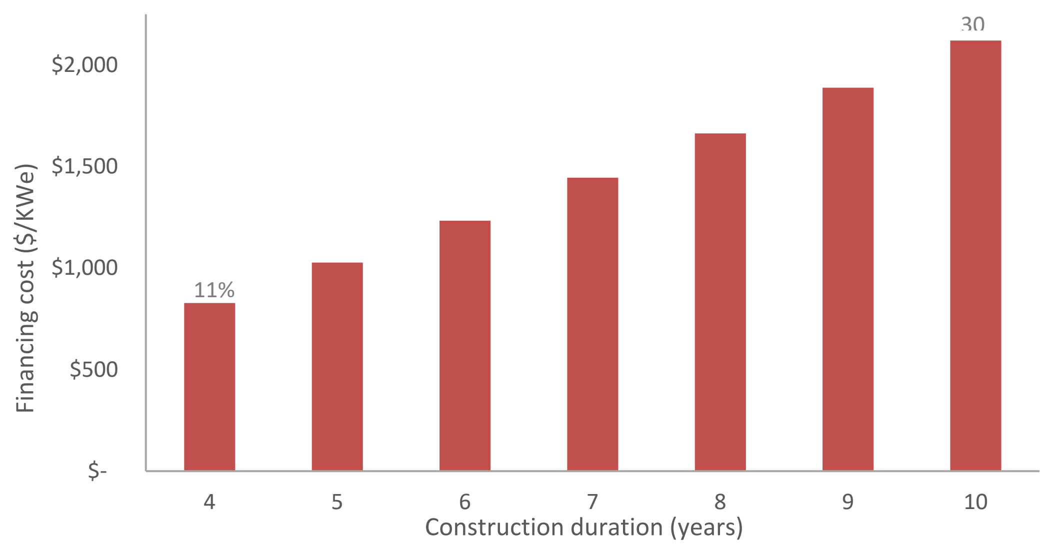

Figure 3-1. Financing cost versus construction duration (conventional LWR)

Construction Duration Versus Overnight Cost

In analyzing capital costs of NPPs, it is necessary to establish a relationship between overnight cost and construction duration, as some components of EPC costs are positively correlated with construction duration. Research from Stewart et al. [8] on construction duration of advanced nuclear plants describes this relationship. An increased construction duration typically implies an increase in engineering and field labor costs due to rework, additional licensing costs due to regulatory issues, and other home office costs, such as project controls. Accordingly, EPC costs tend to scale linearly as construction duration increases.

Figure 3-2 displays simulated EPC costs and construction duration pairs for a generic conventional LWR. In this example, the positive correlation between construction duration and EPC costs results in a 20% increase in overnight costs for an NPP with a construction duration of 10 versus 4 years.

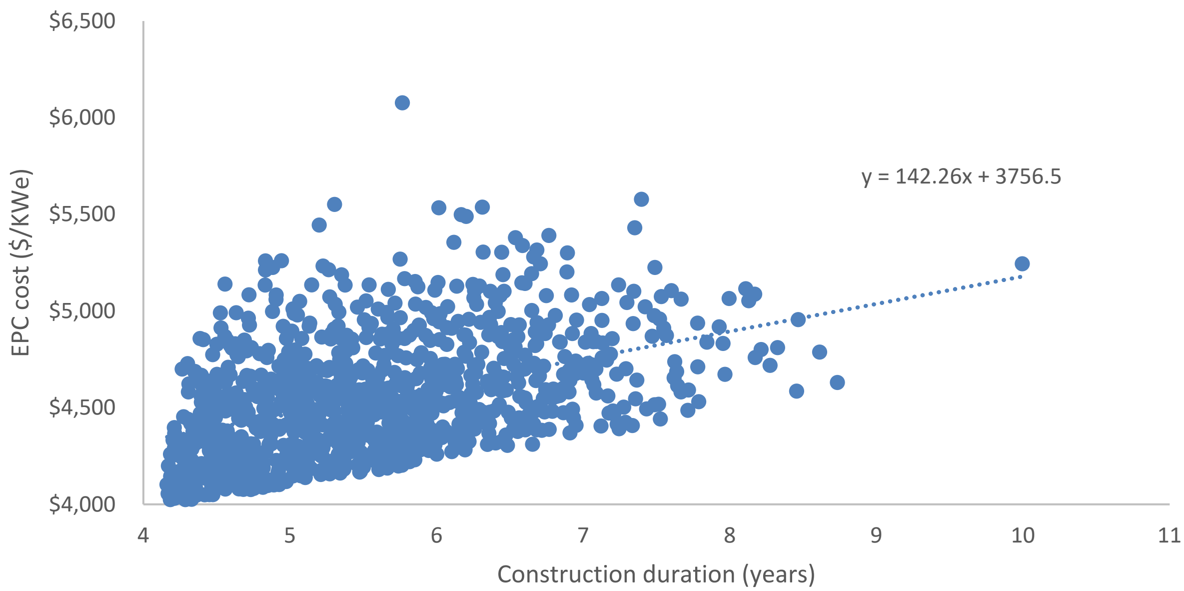

Figure 3-2. Construction duration versus EPC cost (conventional LWR)

Overall Effect of Construction Duration on Capital Cost

Figure 3-3 combines the effects of construction duration on financing and overnight costs to show the overall effect on capital cost. Using the example of a generic conventional LWR with an overnight cost of $5,050/KWe and an effective cost of capital of 6.3%, the model shows capital cost rising from $6,043/KWe to $8,811/KWe—an increase of 46%—given construction durations of 4 and 10 years, respectively. Financing cost is the dominant driver, increasing by $1,754/KWe versus $1,014/KWe for overnight costs. This example highlights the profound effect of construction duration on capital costs and how NPPs with higher overnight costs but shorter construction durations can potentially have lower overall capital costs.

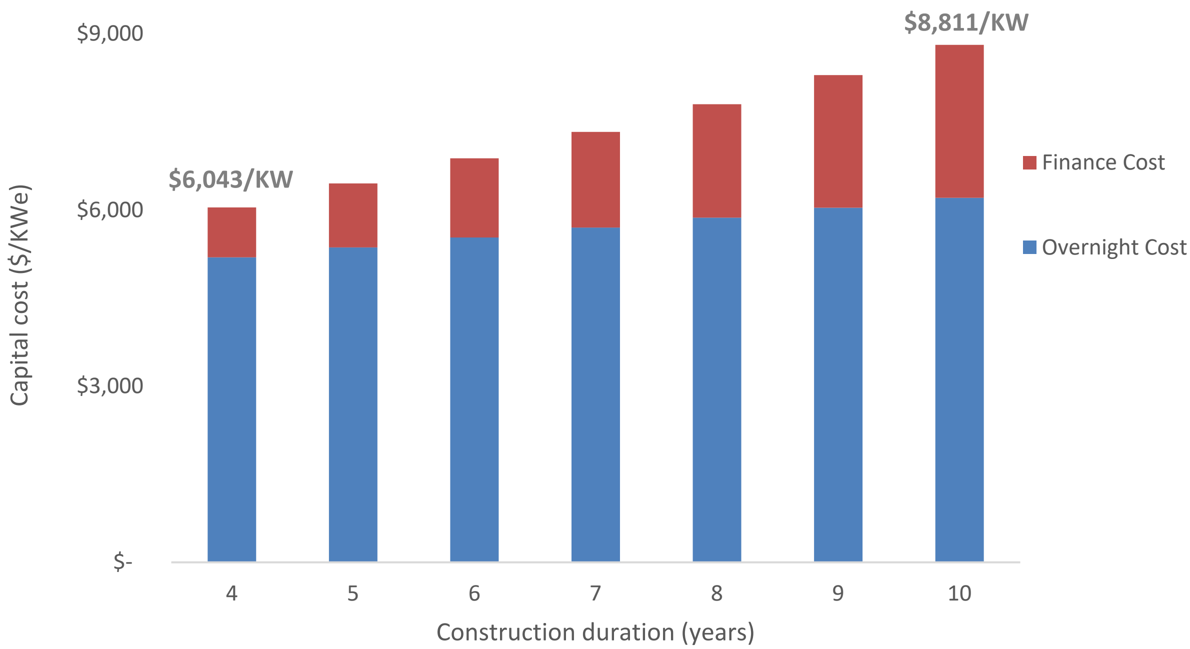

Figure 3-3. Construction duration versus capital cost (conventional LWR)

4 EFFECT OF COST OF CAPITAL ON NPP CAPITAL COSTS

Financing Cost Versus Cost of Capital

Figure 4-1 shows the effects of increasing the cost of capital for a generic NPP with an overnight cost of $5,050/KWe and construction duration of 5 years. At a cost of capital of 3%, financing cost is only $415/KWe or 8% of capital costs, but at a cost of capital of 10%, financing cost jumps to $1,536/KWe or 23% of capital costs.

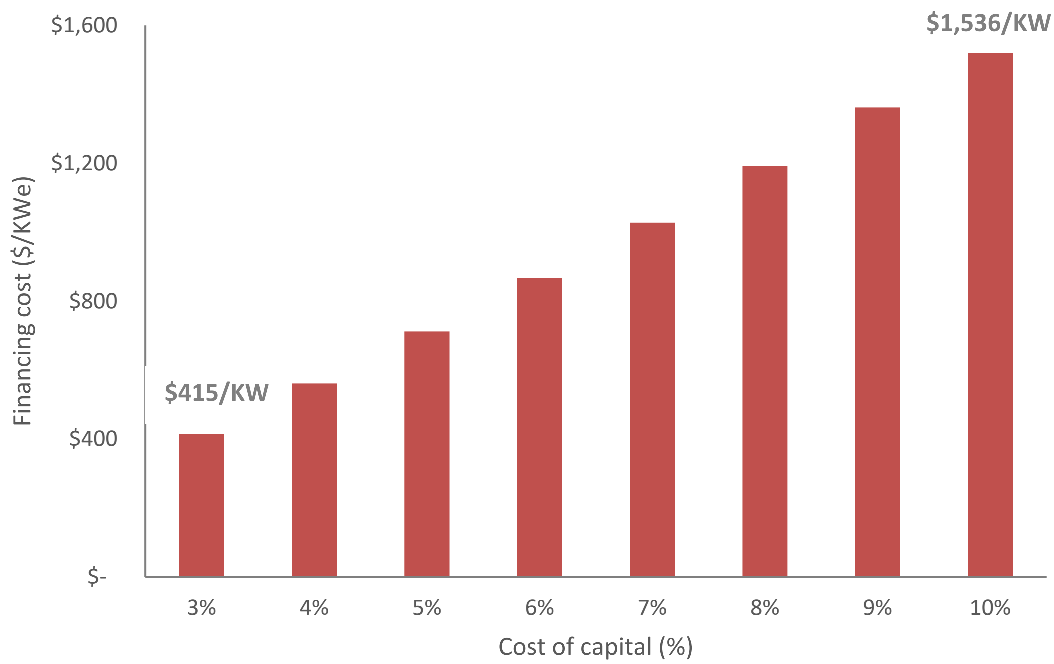

Figure 4-1. Financing cost versus cost of capital

While this relationship is relatively obvious, it is worth further exploring:

- How NPPs are financed
- Cost of capital drivers for different NPP designs
- Financing mechanisms used to lower the cost of capital

Factors Affecting Cost of Capital

Cost of capital for NPPs is largely driven by three key risks: revenue risk, cost risk, and completion risk.

Revenue Risk

Revenue risk is the risk that the power generated by an NPP after commercial operation has a value that is uncertain and that is lower than expected when the investment decision was made.

If revenue is low, an operating nuclear power project may not cover cost of financing (i.e., debt service) and generating costs. A nuclear project that cannot meet debt service may have to refinance its debt, with a likely higher interest rate and increased equity level.

In the extreme case, the lower revenue may lead the NPP owner to close the plant early (i.e., before the end of the plant's operating license) to stop financial losses. This is what happened to multiple U.S. merchant NPPs (e.g., Kewaunee [9], Vermont Yankee [10], and others).

It is unclear that SMR projects will have different revenue risks than large LWR projects. Some features of SMR projects that might help mitigate revenue risk include:

- Operating flexibility, which would allow the plant to lower output during low market price periods (e.g., nights)
- Generating costs that are more variable (e.g., some advanced reactor designs have continuous fueling and may have nuclear fuel cost that is marginal)

Cost Risk

Cost risk is the risk that the project costs will be greater than expected. Even if everything else in the project (i.e., time to build, operating performance, and revenue after commercial operation) meets expectations, a higher capital cost will mean that project financial returns are lower than expected when the investment decision was made.

The project may be able to raise additional capital to complete the project and reach commercial operation (e.g., by taking on more project debt and equity), but this will likely mean a higher interest rate for debt, an increased amount of equity, or both.

Virtually all U.S. NPPs have seen increases in costs since the onset of commercial deployment. Table 4-1 captures the cost overruns for U.S. NPPs.

Table 4-1. Historical Project Versus Actual Overnight Costs [11]

Year construction was initiated	Number of plants started	Average utility projections of overnight costs ($/KWe)[3]	Average actual overnight costs ($/KWe)	Overrun (%)
1966–1967	11	612	1279	109
1968–1969	26	741	2180	194
1970–1971	12	829	2889	248
1972–1973	7	1220	3882	218
1974–1975	14	1263	4817	281
1976–1977	5	1630	4377	169

There may be several ways that an SMR nuclear power project could have lower cost risk than a large LWR:

- Shorter construction time that lowers the potential for cost increases
- Modular designs with off-site manufacturing that lower the level of construction activity and risk
- Simpler designs that require fewer components and less on-site craft labor

Completion Risk

Completion risk is the risk that the project will not be completed and will be abandoned prior to commercial operation. In this situation, the capital investment up to the point of abandonment is spent, but there is no operating revenue to provide a return on this capital investment. It may be possible for the project owner to recover some of the capital investment by, for example, selling major components or making litigation/arbitration claims against EPC contractors or major equipment suppliers.

The reasons why a nuclear power project might be abandoned include:

- Cost to build is higher than expected.
- Time to build is longer than expected.
- There is an unexpected level of public opposition to the project.

[3] Data in source document provided in thousands of dollars per MWe. Units converted to $/KWe for consistency with data in this report.

- The market for power that would be generated by the project after completion significantly changes during construction.
- There are problems with the NPP design that require major rework.

Examples of projects that experienced completion risk include V.C. Summer 2 and 3 in South Carolina [12], Shoreham in New York [13], Zwentendorf in Austria [14], and Montalto di Castro in Italy [15].

SMR projects may have similar levels of completion risk as large LWR projects. However, some features of SMR projects may help lower and/or mitigate completion risk include:

- Shorter construction time that lowers the potential for cost increases
- Modular designs with factory manufacturing that lower the level of construction activity and risk
- Simpler designs that require fewer components and less on-site craft labor
- A standard reactor design (i.e., rather than the unique designs seen in large LWR projects) that lowers the potential for construction and licensing issues

5 SIMULATING CAPITAL COSTS OF CONVENTIONAL REACTORS AND SMRS

As discussed in the previous sections, various differences between conventional LWRs and SMRs can significantly affect capital costs, especially financing costs. To further analyze this question, two scenarios were modeled to compare conventional LWRs and SMRs across a standard project size:

- First of a kind (FOAK) LWR and SMR (1000 MWe)
  - Assumes FOAK technology and associated cost profile
  - Assumes 1000 MWe total plant output for both LWR and SMR cases
  - Assumes a single generic conventional LWR
  - Assumes multiple generic SMRs constructed in parallel
- Nth of a kind (NOAK) LWR and SMR (1000 MWe)
  - Assumes mature technology and associated cost profile
  - Assumes 1000 MWe total plant output for both LWR and SMR cases
  - Assumes a single generic conventional LWR
  - Assumes multiple generic SMRs constructed in parallel

One thousand Monte Carlo simulations of capital cost and the respective inputs were run for each scenario. Each simulation presents the probability distribution function for capital cost, overnight cost, financing cost, EPC cost, construction duration, and cost of capital.

The following sections discuss the various inputs used in the model and the results of the Monte Carlo simulations covering the FOAK and NOAK scenarios.

Overnight Costs Used in Analysis

Many studies, reports, and estimates explore overnight costs for both FOAK and NOAK NPPs of various designs. Stewart and Shirvan note that methodologies and cost estimates vary significantly among different reports [15]. Rather than focusing on one specific estimate for the analysis, the team surveyed a range of sources and pooled the results for an aggregate overnight cost representing generic FOAK and NOAK LWRs and SMRs. Owner’s cost was assumed to be a constant 20% of EPC cost for all scenarios. Table 5-1 lists the overnight costs used in the analysis.

Table 5-1. Overnight Costs Used in Analysis (2022 USD) [16, 17, 18, 19]

Reactor type	FOAK cost	NOAK cost
LWR	$9,450/KWe	$5,050/KWe
SMR	$8,460/KWe	$5,134/KWe

Construction Duration Used in Analysis

Similar to the approach for overnight costs, the analysis relied on pooled results from various studies, reports, and vendor estimates to develop aggregate construction durations for generic FOAK and NOAK LWRs and SMRs. Table 5-2 lists the construction durations used in the analysis.

Table 5-2. Construction Duration Used in Analysis [6, 17, 20]

Reactor type	FOAK duration	NOAK duration
LWR	7.5 years	5 years
SMR[4]	4.5 years	3 years

Cost of Capital Used in Analysis

As described in Section 1, cost of capital is the weighted average of the cost of equity and cost of debt. For modeling purposes, a 20/80 debt-to-equity ratio was assumed in all scenarios. Cost of equity (12.7–15.4%) was estimated using the capital asset pricing model (CAPM)[5], and cost of debt (4.25–6.5%) was assumed based on risk profiles of the various NPP designs under analysis. Overall, costs of capital for FOAK builds were identical, and a slight discount was modeled for NOAK SMRs for reasons discussed in Section 4. Table 5-3 lists the cost of capital values used in the analysis.

Table 5-3. Cost of Capital Used in Analysis

Reactor type	FOAK cost of capital	NOAK cost of capital
LWR	8.2%	6.4%
SMR	8.2%	5.9%

[4] SMR construction durations were informed by interviews with SMR vendors.

[5] CAPM calculates the expected return of an investment based on the risk premium—that is, the rate of return greater than the risk-free rate.

Modeling Capital Costs

To assess capital costs of different NPPs, a financial model was developed that uniformly distributes overnight costs semiannually over the construction duration for a given NPP. These costs are adjusted to nominal values by accounting for inflation (assumed flat 2.5%). Financing costs are next calculated by multiplying the outstanding period balance by the cost of capital. Overnight costs and financing costs are then discounted back to 2022 dollars using the present value of the future cash flows to allow for baseline comparison across plants. Table 5-4 provides an example of the financial model for an NOAK SMR with overnight costs of $5,134/KWe and a construction duration of 3 years.

Table 5-4. Representative Financial Model

Year	0	0.5	1	1.5	2	2.5	3
Nominal overnight costs ($/KWe)	856	866	877	888	899	910	0
Nominal finance costs ($/KWe)	0	25	52	79	108	138	169
Nominal capital costs ($/KWe)	856	1,747	2,676	3,643	4,650	5,698	5,867
Present-value overnight costs ($/KWe)	5,134						
Present-value finance costs ($/KWe)	541						
Present-value capital costs ($/KWe)	5,675						

For comparative analysis of different NNPs, truncated normal distribution multipliers were applied to overnight cost and construction duration, and 1000 Monte Carlo simulations per scenario were run to account for variability and uncertainty in model inputs (a normal distribution multiplier was applied to cost of capital). For each Monte Carlo simulation, an additional multiplier was applied to overnight cost and construction duration to account for the positive correlation between the two variables, as discussed in Section 3. By modeling variation and uncertainty in inputs, the results capture a probability distribution for capital costs and its various drivers. This approach allows for relative comparison across different NPPs, and the risk profile associated with each project is visualized in Figure 5-1 and Figure 5-2.

FOAK LWR Versus SMR (1000 MWe)

Figure 5-1 shows the Monte Carlo simulations comparing a 1000 MWe FOAK LWR and SMR. Average capital costs for the SMR are 16% lower than the LWR, primarily driven by lower financing costs resulting from shorter construction durations. Additionally, the probability distribution for capital costs of the SMR shows a lower risk of cost overruns relative to the LWR.

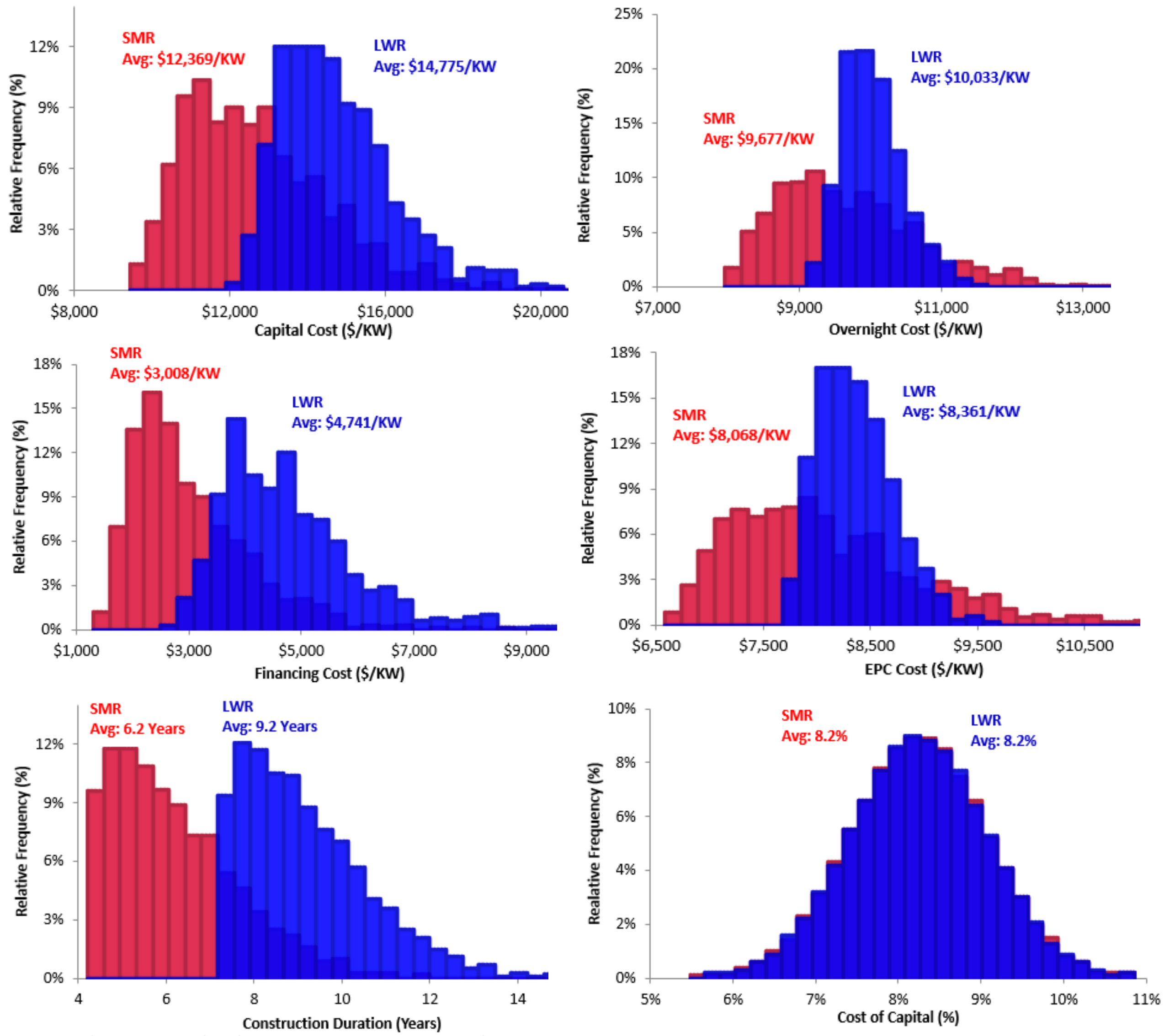

Figure 5-1. Monte Carlo simulation of 1000 MWe FOAK LWR and SMR

NOAK LWR Versus SMR (1000 MWe)

Figure 5-2 shows the Monte Carlo simulations comparing a 1000 MWe NOAK LWR and SMR. Average capital costs for the SMR remain lower than that of the LWR, but only by 5%. In this scenario, overnight cost is higher for the SMR, but lower financing costs continue to drive an overall lower capital cost. Additionally, the probability distribution for capital costs is similar between the SMR and LWR, implying a similar risk profile for the NOAK projects. Of note, a slight discount to cost of capital was applied to the SMR (5.9% vs. 6.4%) for project risk considerations discussed in Section 4.

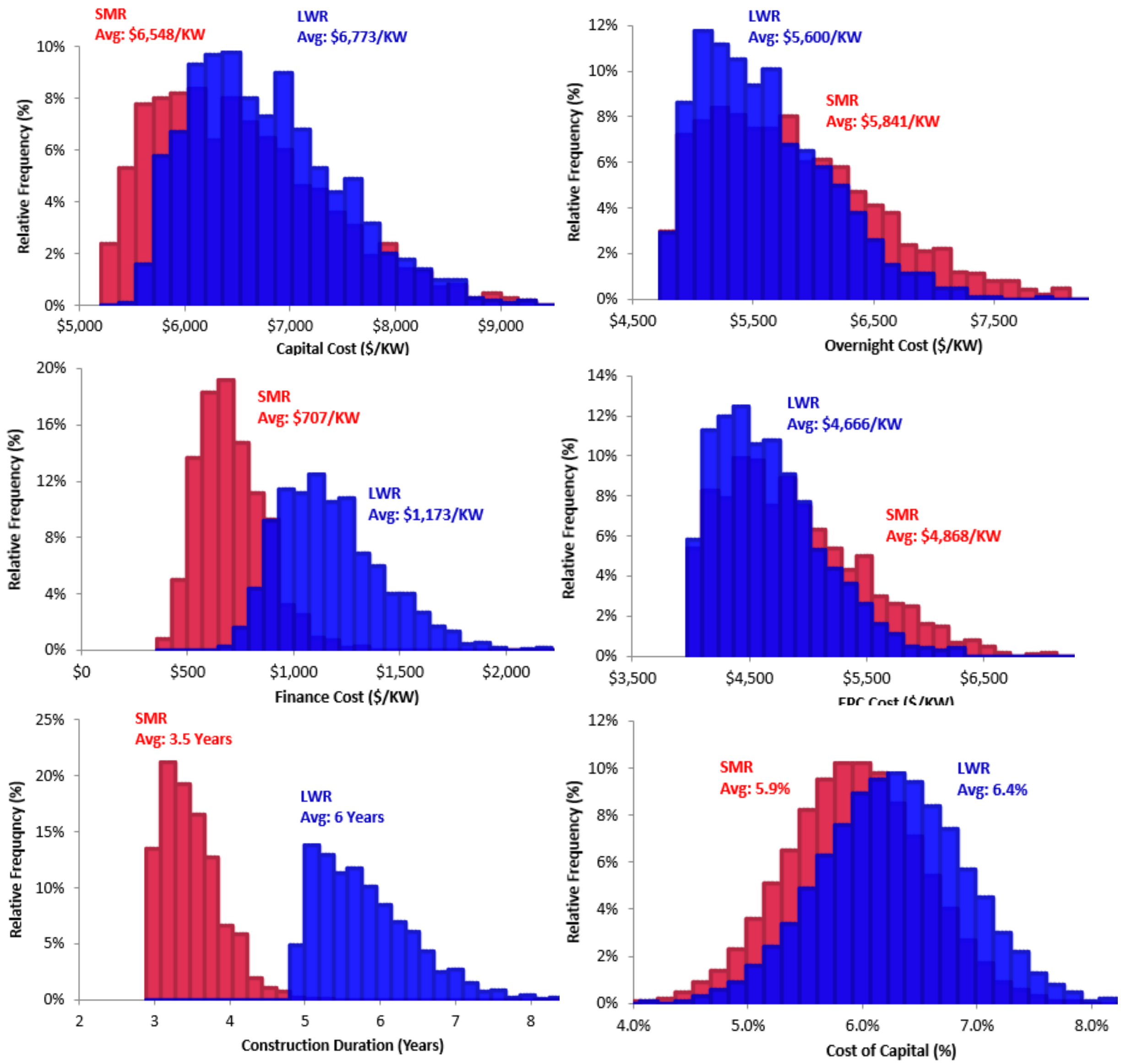

Figure 5-2. Monte Carlo simulation of 1000 MWe NOAK LWR and SMR

Sensitivity Analysis

To further compare the NOAK SMR and LWR, a sensitivity analysis was conducted by shifting the distributions for overnight cost (EPC + owner's costs), construction duration, and cost of capital by +/−25% to represent high and low scenarios (Table 5-5). In all instances, except for the low cost of capital scenario, the NOAK SMR has lower capital costs than the NOAK LWR. Financing costs again are the main differentiator, but the SMR and LWR NOAK projects continue to be competitive throughout the sensitivity analysis, with the max spread in capital costs between the NOAK NPPs at $425/KWe.

Table 5-5. Sensitivity Analysis of NOAK NPPs

	NOAK LWR—1000 MWe			NOAK SMR—1000 MWe		
Overnight cost (+/−25%)						
	Low	Base	High	Low	Base	High
Overnight cost	$4,310/KWe	$5,600/KWe	$6,890/KWe	$4,532/KWe	$5,841/KWe	$7,153/KWe
Financing cost	$870/KWe	$1,173/KWe	$1,497/KWe	$533/KWe	$707/KWe	$896/KWe
Capital cost	$5,180/KWe	$6,773/KWe	$8,387/KWe	$5,065/KWe	$6,548/KWe	$8,049/KWe
Construction duration (+/−25%)						
	Low	Base	High	Low	Base	High
Const. duration	4.5 years	6.0 years	7.1 years	2.7 years	3.5 years	4.3 years
Overnight cost	$5,394/KWe	$5,600/KWe	$5,806/KWe	$5,627/KWe	$5,841/KWe	$6,056/KWe
Financing cost	$889/KWe	$1,173/KWe	$1,484/KWe	$551/KWe	$707/KWe	$886/KWe
Capital cost	$6,283/KWe	$6,773/KWe	$7,290/KWe	$6,178/KWe	$6,548/KWe	$6,942/KWe
Cost of capital (+/−25%)						
	Low	Base	High	Low	Base	High
Cost of capital	3.00%	6.40%	9.00%	3.00%	5.90%	9.00%
Overnight cost	$5,600/KWe	$5,600/KWe	$5,600/KWe	$5,841/KWe	$5,841/KWe	$5,841/KWe
Financing cost	$528/KWe	$1,173/KWe	$1,775/KWe	$348/KWe	$707/KWe	$1,109/KWe
Capital cost	$6,128/KWe	$6,773/KWe	$7,375/KWe	$6,189/KWe	$6,548/KWe	$6,950/KWe

Overall, the NOAK simulation and sensitivity analysis show that the NOAK SMR can have an 8% premium in overnight cost compared to the NOAK LWR ($6,039/KWe vs. $5,600/KWe) and still have the same capital cost and risk profile largely because of savings in financing costs.

6 NPP FINANCING METHODS

Because of the risk and previous history of NNP construction, traditional financing mechanisms used in other energy infrastructure projects are typically not used to finance nuclear projects. This section discusses alternative financing methods commonly used in nuclear projects today.

Government Financing

Governments may provide assistance to NPPs through government loans, loan guarantees, or direct financing. This is often done because of the risk associated with these projects and the public benefit that they provide. Government financing has been the traditional approach to funding NPPs and has been used in China, France, India, South Korea, Russia, the United Arab Emirates (UAE), and the United States. In China, for example, Qinshan 1 and 2 projects were financed directly from the government budget, and in the UAE, Barakah NPP received sovereign loan guarantees from both the UAE and South Korean governments [21].

Another well-known model is the U.S. Loan Guarantee Program, which was authorized under the Energy Policy Act (EPAct) of 2005 and is discussed in detail below. Under the U.S. Loan Guarantee Program, nuclear owners may submit an application to the Department of Energy (DOE) for nuclear projects employing new or significantly improved technology. Approved projects will receive conditional DOE commitment to guarantee loans made by the Federal Financing Bank (FFB), a government corporation that is part of the U.S. Treasury Department and operates as a wholesale lender to federal agencies and various federally approved projects. DOE-guaranteed loans issued by the FFB under the EPAct typically have 20- to 30-year maturities and bear interest at the applicable U.S. Treasury rate plus small spread.

SMR projects should be able to take advantage of the DOE Loan Guarantee Program, but it is unclear how or if the subsidy fee approach and level will reflect different levels of project risk linked to SMR reactor designs.

Corporate Financing

Another approach to finance a new nuclear power project is to fund the project as a part of a larger corporation's balance sheet. In effect, the corporate owner internalizes nuclear project risk and can raise debt and equity based on the larger corporate entity's lower cost of capital, as opposed to facing cost of capital for a stand-alone nuclear project.[6]

[6] Note that the significant risk of a new nuclear power project has meant that no nuclear power project has used the project finance techniques that have become common in nonnuclear power projects.

The large size and large capital cost of a conventional LWR NPP project may make such an approach difficult for even a large corporate entity. Even if it is possible, the impact of a large LWR project on a corporate owner's financial situation is likely to be significant.

Accordingly, the smaller size and smaller capital cost of an SMR NPP project may increase the potential for financing a nuclear power project on a corporation's balance sheet.

Vendor Financing

As reactor vendors look to make sales, some of them may include offers of financing in the form of equity investments, share of project debt, or both. This approach has been seen mostly outside the United States.

The leading example of vendor funding is the Russian approach to NPP export sales, where the Russian government makes government-to-government loans to a country with the proceeds used to buy Russian nuclear plants. This is the approach underlying the Russian NPP projects now under construction in Egypt and Bangladesh.

Another example is the sale of French reactors to China, the Taishan EPR projects, which included a 30% equity investment by Électricité de France.

There is no sign that the existence or level of vendor financing will depend on whether a nuclear power project is a large LWR project or an SMR project.

7 CONCLUSION

This report has performed an analysis to determine the effect of financing costs on overall capital costs for both conventional LWRs and SMRs.

The conclusion of this report is that when deciding between different classes of nuclear technology that have construction durations and cost of capital, total capital costs—including both overnight and financing costs—should be used as input to technology selection as opposed to just overnight cost alone.

Utilizing a probabilistic approach can provide additional insights with regard to schedule and cost risk for input into decisions on deploying capital for new nuclear plant projects.

8 REFERENCES

1. IEA and NEA. *Projected Costs of Generating Electricity*. International Energy Agency, 2020.
2. W. D'haeseleer, "Synthesis on the Economics of Nuclear Energy." European Commission, DG Energy, 2013.
3. Y. Du and J. Parsons, "Update on the Cost of Nuclear Power." MIT Center for Energy and Enviromental Policy Research, 2009.
4. MIT Energy Initiative, "The Future of Nuclear Energy in a Carbon-Constrained World." Massachusetts Institute of Technology, 2018.
5. World Nuclear Association. *Nuclear Power Economics and Project Structuring*. 2017.
6. P. Carajilescov and J. Moreira, "Construction Time of PWRs." 2011.
7. Georgia Power. *Twenty-seventh Semi-annual Vogtle Construction Monitoring Report*. 2022.
8. W. Stewart, J. Gegory, and K. Shirvan, "Construction Duration Estimation for Advanced Nuclear Power Plants." 2022.
9. M. Wald, "As Price of Nuclear Energy Drops, a Wisconsin Plant Is Shut." *The New York Times*, 2013.
10. J. Bidgood, "Vermont Yankee Nuclear Plant Begins Slow Process of Closing." *The New York Times*, 2015.
11. B. Plumer, "U.S. Nuclear Comeback Stalls as Two Reactors Are Abandoned." *The New York Times*, 2017.
12. "Dismantling of the Shoreham Nuclear Plant Is Completed." *The New York Times*, 1994.
13. P. Weish, "Austria's No to Nuclear Power." University of Vienna, Austria, 1988. https://homepage.univie.ac.at/peter.weish/schriften/austrias_no_to_nuclear_power.pdf
14. World Nuclear Association, "Nuclear Power in Italy." 2022. https://world-nuclear.org/information-library/country-profiles/countries-g-n/italy.aspx
15. W. R. Stewart and K. Shirvan, "Capital Cost Estimation for Advanced Nuclear Power Plants," *Renewable and Sustainable Energy Reviews*, vol. 155 (2022).
16. K. Shirvan, "Overnight Capital Cost of the Next AP1000." MIT Center for Advanced Nuclear Energy Systems, 2022.
17. Energy Information Administration. *Annual Energy Outlook*. 2022.
18. G. Black, F. Aydogan, and C. L. Koerner, "Economic Viability of Light Water Small Modular Nuclear Reactors: General Methodology and Vendor Data," *Renewable and Sustainable Energy Reviews*, vol. 103, pp. 248–258 (2019).
19. International Atomic Energy Agency. *Status Report 83—Advanced Power Reactor 1400 MWe* (APR1400). 2011.

21. Municipal Electric Authority of Georgia. *2021 Annual Report*. 2021.

22. International Atomic Energy Agency. *Financing Nuclear Power in Evolving Electricity Markets.* 2018.

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