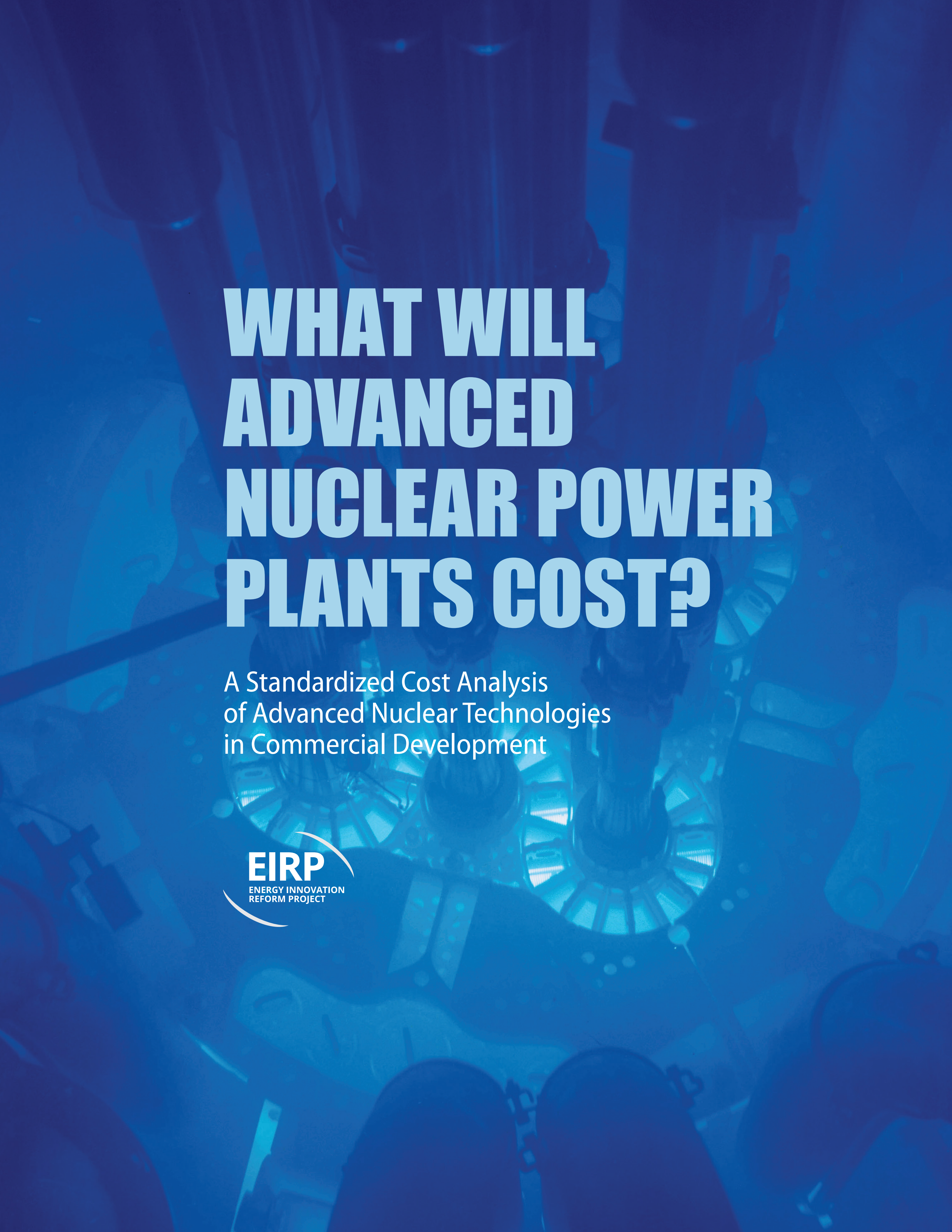

WHAT WILL ADVANCED NUCLEAR POWER PLANTS COST?

A Standardized Cost Analysis of Advanced Nuclear Technologies in Commercial Development

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AN ENERGY INNOVATION REFORM PROJECT REPORT
PREPARED BY THE ENERGY OPTIONS NETWORK

ENERGY OPTIONS
NETWORK

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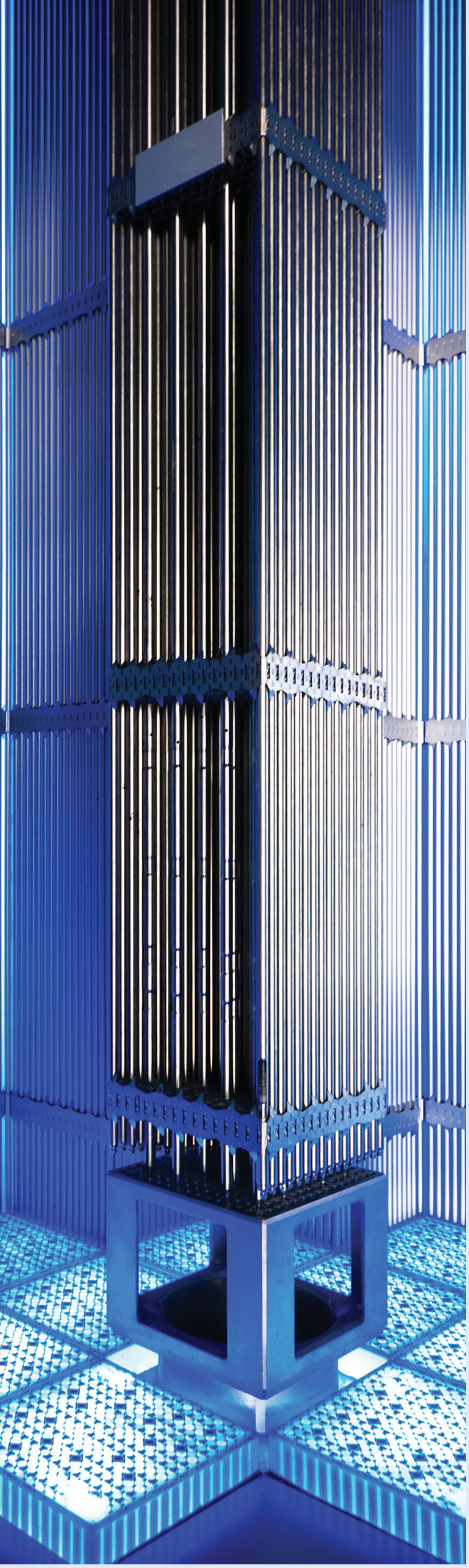


EXECUTIVE SUMMARY

Advanced nuclear technologies are controversial. Many people believe they could be a panacea for the world's energy problems, while others claim that they are still decades away from reality and much more complicated and costly than conventional nuclear technologies. Resolving this debate requires an accurate and current understanding of the increasing movement of technology development out of national nuclear laboratories and into private industry. Because the work of these private companies is proprietary, they have relatively little incentive to make information public, and the absence of credible information about these technologies and their potential costs gives credence to the claims of nuclear skeptics.

Advanced nuclear technologies represent a dramatic evolution from conventional reactors in terms of safety and nonproliferation, and the cost estimates from some advanced reactor companies—if accurate—suggest that these technologies could revolutionize the way we think about the cost, availability, and environmental consequences of energy generation. Skepticism about the cost of future nuclear technologies is understandably high, given the infamously unmet promise of energy "too cheap to meter."

Assessing the claims of technology developers on a standardized basis, as much as possible, is vitally important for any fact-based discussion about the future cost of nuclear. Previous work by the Energy Options Network (EON) found that each company had its own approach to estimating plant costs, making true "apples-to-apples" comparisons with conventional pressurized water reactors (PWRs) impossible. This study was designed to address that deficiency.

Comparing the cost of future nuclear technologies to current designs (or other generation technologies) requires capturing cost data for advanced nuclear plants in a standardized, comprehensive manner. Using the plant cost accounting framework developed by the Generation IV International Forum, EON created a cost model for this study that includes all potential cost categories for an nth-of-a-kind (NOAK) nuclear plant. It includes default values for each cost category (based on previous cost studies conducted at national laboratories), and provides capability for companies to incorporate new business models and delivery strategies.

Using this model, EON worked with leading advanced reactor companies to obtain reliable, standardized cost projections for their NOAK plants. Advanced nuclear companies that are actively pursuing commercialization of plants at least 250 MW in size were invited to join this study; the eight that were able to participate are listed in table 1. The intent was to focus on reactor and plant sizes that could have a significant role in utility-scale power generation.[1]

1. Several advanced reactor companies are developing small reactors (< 30 MW) to serve off-grid/remote communities and industries. While serving these markets offers a viable commercialization strategy for new reactor technologies, the markets are niche and more tolerant of smaller, higher-cost plants. Some of these developers are considering grid-scale plants, but they were not prepared to provide NOAK cost estimates based on their technology at this time.

Table 1. Study Participants

Company	Reactor Type[a]	Country	Reactor Capacity (MWe)	Plant Capacity (MWe)
Elysium Industries	MSR	U.S.	1,000	1,000
General Electric[b]	SFR	U.S.	1,648	1,648
Moltex Energy	MSR	U.K.	1,000	1,000
NuScale Power	APWR	U.S.	47.5	570
Terrestrial Energy	MSR	Canada	288	288
ThorCon Power[c]	MSR	U.S.	250	1,000
Transatomic Power	MSR	U.S.	520	520
X-energy	HTGR	U.S.	75	600

Note: TerraPower and GE-Hitachi declined to participate in the study (see note below regarding GE PRISM cost information).

a. Advanced nuclear reactor types are described in section 4 of this report.

b. Information is based on publicly available cost studies for the GE PRISM reactor. During the course of this study, GE-Hitachi and Advanced Reactor Concepts were negotiating the terms of a joint venture to develop a sodium-cooled small modular reactor. The GE-Advanced Reactor Concepts project is not included in this study.

c. Costs are based on the company's ThorConIsle design.

Anonymized NOAK plant costs from all participating companies are summarized in table 2 and figures 1, 2, and 3. As shown, advanced nuclear companies are projecting cost targets that, if achieved, would be nearly half the cost of conventional nuclear plants.[2] This would dramatically improve nuclear's value proposition and offer a highly cost competitive alternative to other baseload options. At the lower end of the potential cost range, these plants would be the lowest-cost generation sources available.

Table 2. Cost Summary for All Participating Companies

	Average	Minimum	Maximum
Capital cost total	$3,782/kW	$2,053/kW	$5,855/kW
Operating cost total	$21/MWh	$14/MWh	$30/MWh
Levelized cost of electricity	$60/MWh	$36/MWh	$90/MWh

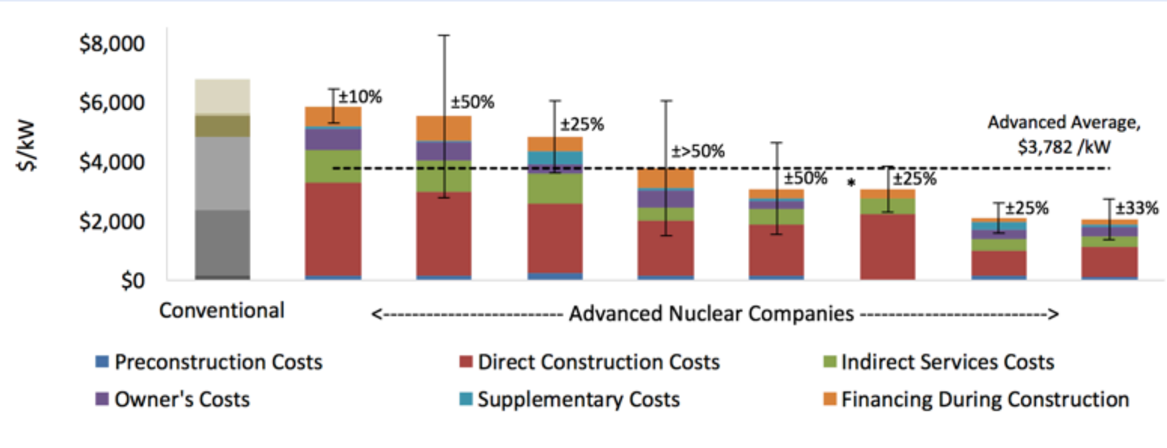
The average levelized cost of electricity (LCOE) of $60/MWh from our study participants is 39 percent lower than the $99/MWh expected by the U.S. Energy Information Agency for PWR nuclear plants entering service in the early 2020s (EIA 2017b).

This finding has important strategic implications for the industry and the nation. While recognizing the relatively early state of development for these technologies, this study nevertheless represents an initial, rigorous quantification of the plausible projected costs of power plants built with advanced reactors. Previously, concerns about data quality and breadth sharply limited efforts to assess these technologies.

If power plants featuring these technologies are able to produce electricity at the average LCOE price projected here (much less the low-end estimate), it would have a significant impact on electricity markets. In the United States, these technologies could be the definitive solution for the economic woes of nuclear energy in merchant markets. At these costs, nuclear would be effectively competitive with any other option for power generation. At the same time, this could enable a significant expansion of the nuclear footprint to the parts of the world that need clean energy the most—and can least afford to pay high price premiums for it.

2. As shown in table 2, the average total capital cost for advanced nuclear is $3,782/kW. This is 56 percent of the PWR benchmark cost of $6,755/kW (described in section 4). The benchmark PWR cost is consistent with recent estimates for the two nuclear projects under construction in the United States, V.C. Summer and Vogtle, which are expected to cost $6,247/kW and $7,586/kW respectively (see section 4 for details).

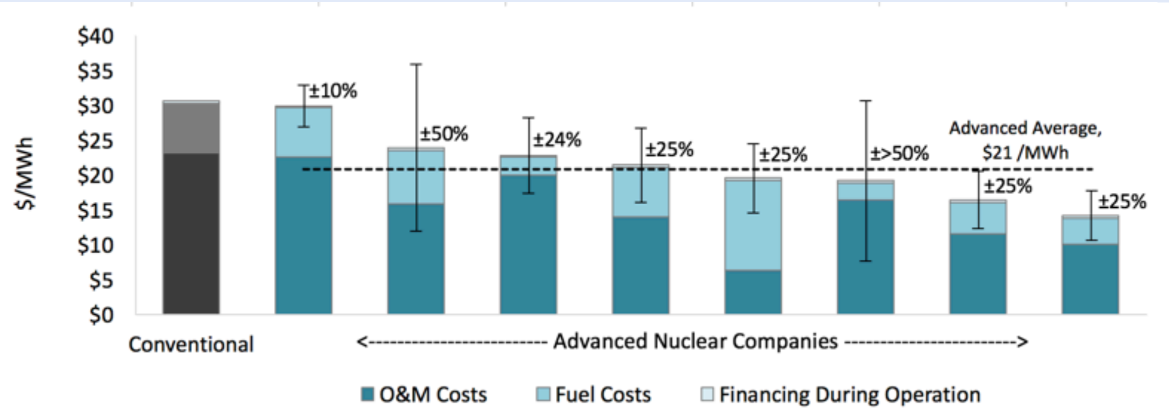
Figure 1. Capital Costs for All Participating Companies



Note: Error bars reflect companies' self-reported confidence bounds.

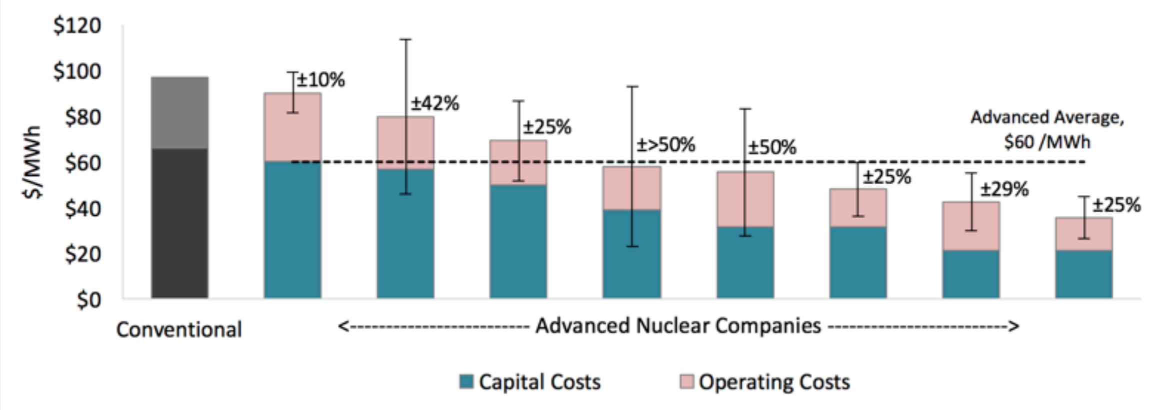
*Company reported costs in such a way that all capital costs (except for indirect services costs) were included in direct construction costs.

Figure 2. Operating Costs for All Participating Companies



Note: Error bars reflect companies' self-reported confidence bounds.

Figure 3. Levelized Cost of Electricity for All Participating Companies



Note: Levelized cost of electricity (LCOE) assumptions include capitalization period of 25 years, discount rate of 7 percent, and capacity factor of 95 percent. Complete details on EON's LCOE calculation are provided in section 4. Error bars reflect companies' self-reported confidence bounds.

While acknowledging the inherent uncertainty in estimating costs for projects that have not yet been built, this study highlights several straightforward, credible strategies that companies are pursuing to achieve their cost projections. The companies surveyed here are combining these strategies to varying degrees, and EON's model was designed to capture the corresponding savings at a granular level. Common cost reduction strategies include the following:

- Simpler and standardized plant designs
- Incorporation of factory- and shipyard-based manufacturing
- Modularization
- Lower materials requirements
- Reduced scope for engineering, procurement, and construction firms
- Shorter construction time
- Higher power density
- Higher efficiency

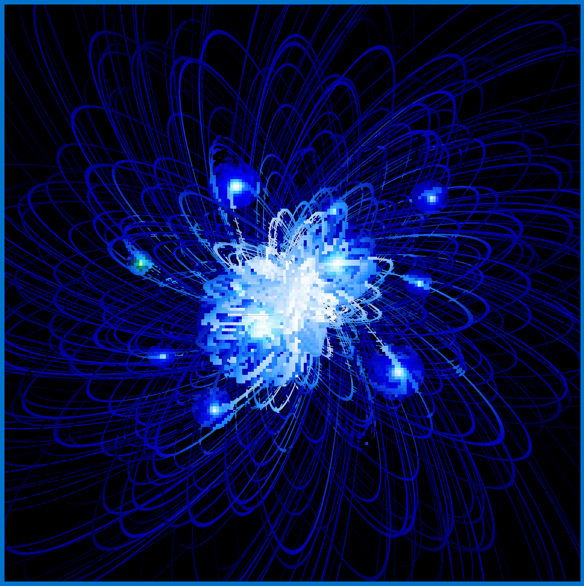
Naturally, there are inherent limitations of a costing exercise for such early stage designs, and there are several reasons why final costs might deviate from these reported estimates. These estimates should not be considered definitive; rather, they are our best reflection of current estimates. The survey also provides useful insights into the strategies that are being used by companies seeking to avoid the pitfalls that have undermined the economics of conventional nuclear generation in the United States and Europe.

Advanced nuclear companies are designing plants that could be highly cost competitive in energy markets driven primarily by economics. Companies have more complete cost estimates than were anticipated, and were able to demonstrate a credible basis for their cost estimates.

Understanding the potential economics of this industry will be important for both investors and policymakers. Most advanced reactor companies have raised only a fraction of the capital necessary for commercial demonstration of their designs, and financing such projects will require new investors and new levels of due diligence. To facilitate that process, it is important to dispel misconceptions on costs and clarify how these companies expect to reach their targets and compete in open markets.

In this regard, this study significantly extends our current level of acuity on a topic that has traditionally been accorded secondary treatment. The prevailing sentiment has been that commercialization of advanced reactors is so far in the future that any discussion of potential costs is premature. The wide range of technologies in this category has also made a comparative discussion difficult. By establishing a common frame of reference and rigorously reviewing the data obtained, this study addresses these analytical challenges and lays the foundation for additional analysis.

1. STUDY MOTIVATION AND OBJECTIVES



Why Care about Advanced Nuclear Costs?

Advanced nuclear technologies could have profound effects on global energy markets—if they are affordable. Advanced nuclear technologies are being pursued not only by national nuclear laboratories but also by a suite of private companies that are understandably reluctant to make information about proprietary work publicly available.[3] The absence of credible information about these technologies and their potential costs makes serious consideration of their potential difficult for policymakers and investors.[4] This study is designed to address that deficiency by providing a standardized format for companies to anonymously provide cost projections, that may be useful for policymakers, investors, and the general public.

Definitive cost studies by Rosner and Goldberg (2011a, 2011b) provide the most recent and comprehensive cost basis costs for (both large and small) modular conventional nuclear plants in the United States. These studies reviewed previous cost studies, regulatory filings, and interviews with subject matter experts to break down estimated overnight costs and examine cost trends. The primary differentiation of this study is that it includes internal cost estimates obtained under nondisclosure agreement by vendors in commercial development. Recognizing that costs are based on design in a relatively early stage, it offers the first advanced reactor cost study informed by vendor-provided estimates.

The future potential of nuclear energy is particularly important in light of current efforts to increase global energy access, reduce all forms of air pollution, and restore U.S. leadership in nuclear energy. Historically, our ability to provide reliable nuclear technologies, fuel, and services to countries—within the context of a strict nonproliferation regime—has been an important source of U.S. influence. This leverage will be significantly weakened if U.S. companies cannot offer the necessary technologies and expertise, forcing other nations to turn to China, Russia, and South Korea (CSIS 2013). A sustained decline in the commercial industry could also have a negative impact on the U.S. nuclear naval program.

3. The U.S. DOE Gateway for Accelerated Innovation in Nuclear (GAIN) program makes DOE's RD&D infrastructure, as well as technical, regulatory, and financial expertise, available to the advanced nuclear sector. The program is designed to expedite technology advancement, and several advanced nuclear companies have made use of the resources available through this initiative.

4. The only comprehensive, publicly available cost studies for advanced nuclear technology have been conducted by national nuclear laboratories. Most of these studies, as listed in the References section of this report, were performed decades ago. With a few exceptions, advanced nuclear companies generally do not provide cost data in their publicly available content. Several industry reports and articles include company-provided costs; however, these costs are not disaggregated and verified as done in this study.

Origins of This Study

In the spring of 2016, EON concluded a 15-month investigation of the advanced nuclear sector, focusing on areas such as the status of reactor design development, business and licensing strategy, strength of engineering teams, and levels of funding. Several companies were developing designs that represented dramatic evolutions in safety and proliferation resistance—and crucially, were estimating potential costs that, if realized, would be revolutionary.

Many of these companies had highly experienced technical teams and credible plans to build a commercial-sized demonstration plant within a decade. Unfortunately, assessing the plausibility and completeness of each company's costs fell outside the scope of work at that time, limiting the value of that initial survey. For such early stage designs, it is impossible to precisely project nth-of-a-kind (NOAK) plant costs, but a more standardized, in-depth assessment of company information could provide a more credible basis for evaluating these claims.[5] This study was designed to meet that need.

A Standardized Framework for Cost Analysis

Our earlier survey revealed that each advanced nuclear company has its own unique approach to estimating plant costs. Some use top-down approaches, while others build costs from the bottom up. We also observed a range in cost sources; some costs referred to prior studies performed at national labs, while others were based on experienced third-party engineering analyses or competitive bid solicitations. Considering these disparate approaches, we believed it was necessary to capture cost data in a standardized, comprehensive manner that allowed for "apples-to-apples" comparisons.

To meet this need, EON developed a cost model template based on vetted accounting criteria for nuclear projects (described in section 3), and worked with advanced reactor companies to obtain information about the projected costs of their NOAK plants. While acknowledging the inherent uncertainty in estimating costs for projects that have not yet been built, this study attempts to highlight the relatively straightforward and seemingly credible cost reduction strategies that companies are pursuing.

The remainder of this report is organized as follows. Section 2 presents the results of this study. Section 3 describes the study's methodology, and section 4 explains the factors behind the results, describing the ways in which advanced nuclear companies are leveraging alternative designs and innovating new business and delivery models to directly solve the shortcomings of conventional nuclear power.

5. NOAK costs assume that many critical and risky development milestones have been met (e.g., licensing the reactor, building a commercial demonstration plant, testing materials, confirming fuel qualifications, etc.), and reflect significant learning curves across the supply chain and plant delivery process. The Economic Modeling Working Group of the Generation IV International Forum (2007) defines NOAK costs as those costs achieved after 8 GWe of capacity has been constructed and where costs decline with each doubling of construction experience (6 percent decrease for equipment costs and 10 percent decrease for construction labor). A fleet size of 32 GWe is necessary to support facilities such as fuel fabrication or reprocessing. Because the companies included in this study are developing plants of different capacities (and some companies assume dedicated manufacturing facilities while others do not), EON did not define a specific number of plants to represent NOAK; we assume NOAK to include plants that participate in competitive bid solicitations; include preselected, experienced vendors and contractors; reflect learning from engineering, manufacturing, and construction; and are delivered on time and within budget.

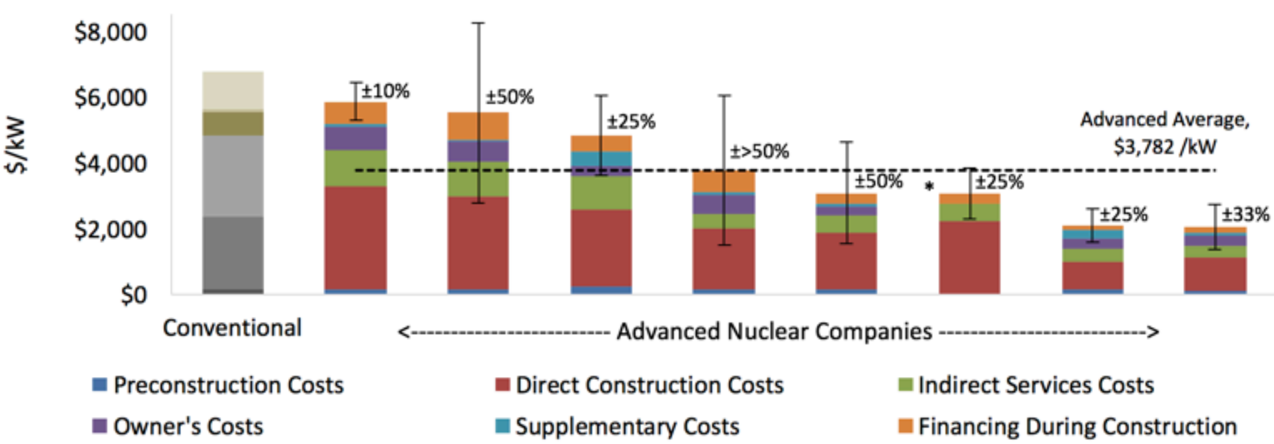
2. RESULTS

This section presents high-level results on advanced nuclear costs based on company submissions. Information has been anonymized, and the order in which company information is presented in figures has been varied, to protect confidentiality. The figures show cost components defined by the single-digit accounts described in appendix A. The figures also include benchmark values for conventional nuclear,[6] and show average values across the participating advanced nuclear companies.

Capital Costs

Figure 4 summarizes capital cost estimates in dollars per kW for the conventional nuclear benchmark and participating advanced nuclear companies. All of the advanced nuclear companies surveyed here have lower total capital cost estimates than the conventional nuclear benchmark. The average total capital cost for the advanced nuclear companies is $3,782/kW, a reduction of $2,973/kW from the conventional nuclear figure of $6,755/kW (see section 4 for details on conventional nuclear costs).

Figure 4. Capital Cost Results



Source: EON analysis of conventional and advanced nuclear cost information as explained in text.

Note: All costs are expressed in 2016 dollars. Error bars reflect companies' self-reported confidence bounds.

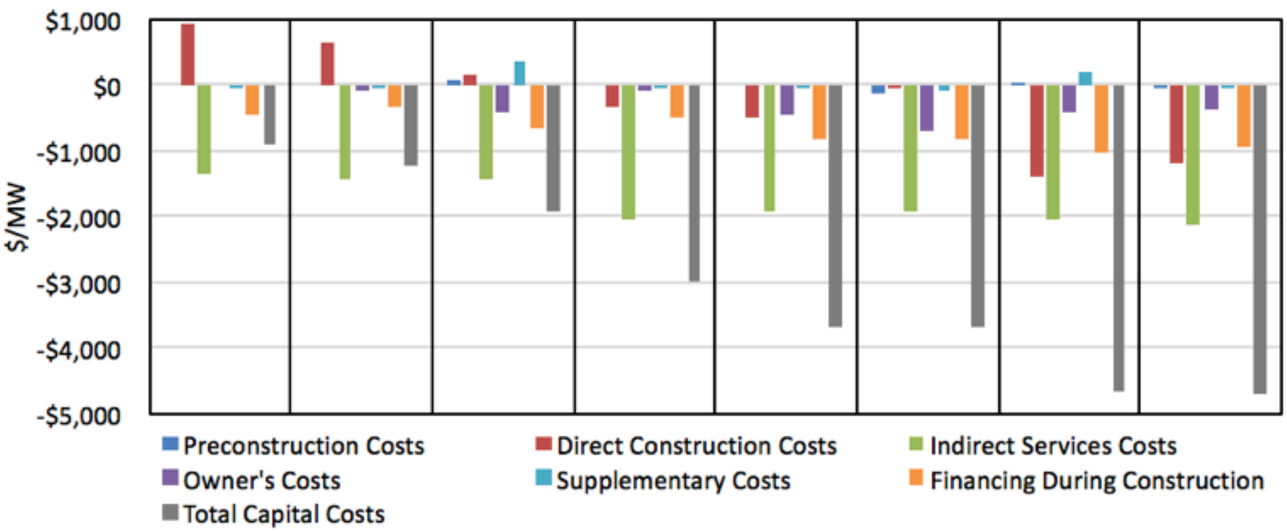
*Company reported costs in such a way that all capital costs (except for indirect services costs) were included in direct construction costs.

As shown in the figure, capital costs consist of preconstruction costs, direct construction costs, indirect services costs, owner's costs, supplementary costs, and financing during construction. Projected capital costs vary based on company-specific design factors, delivery strategies, cost estimation methodologies, and other important factors described in greater detail in section 4. Direct construction cost represents the largest component of capital costs for all companies. For some companies, it exceeds conventional nuclear direct construction costs because of lower power density, larger materials requirements, or other factors. All companies expect significant reductions in indirect services costs. They also expect much lower financing costs during construction because of lower construction expenditures and faster construction schedules (averaging around four years, compared with the assumed duration of seven years for conventional nuclear projects).

6. For this report, the term "conventional" nuclear applies specifically to pressurized water reactors (PWRs), the dominant reactor technology in the United States, and assumes a typical power plant delivery model, as described further below.

Figure 5 shows each advanced nuclear company's capital cost estimates as a difference from the conventional nuclear benchmark by cost category. In the figure, each vertical box represents an advanced nuclear company and the rightmost bar for each company (in gray) is the difference in total estimated capital cost from the PWR benchmark. This total difference is the sum of differences by cost category.

Figure 5. Differences from Conventional Nuclear Capital Costs by Company



Source: EON analysis of conventional and advanced nuclear cost information as explained in text.

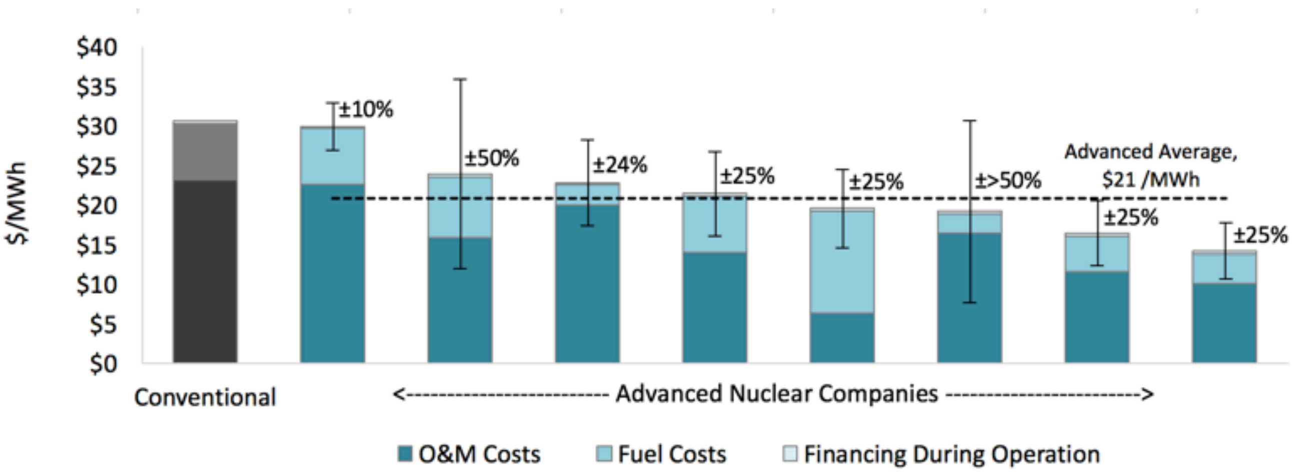
Note: All costs are expressed in 2016 dollars.

As noted above, all advanced nuclear companies have lower total estimated capital costs than the conventional nuclear benchmark. The figure illustrates, however, that some advanced nuclear companies have higher capital costs than the PWR benchmark in some categories, most notably direct construction costs, for the reasons listed above. All advanced nuclear companies have lower indirect services costs primarily due to plant design standardization and more efficient quality assurance and supervision performed at off-site manufacturing facilities (as opposed to on-site construction). They all have lower financing during construction because of lower outlays and faster construction schedules than the conventional nuclear benchmark.

Operating Costs

Figure 6 summarizes operating costs in dollars per MWh for the conventional nuclear benchmark and participating advanced nuclear companies. As with total capital costs, all participating companies have lower total operating cost estimates than the conventional nuclear benchmark. The average total operating cost for the advanced nuclear companies is $21/MWh, a reduction of $10/MWh from the conventional nuclear total of $31/MWh.

Figure 6. Operating Cost Results



Source: EON analysis of conventional and advanced nuclear cost information as explained in text.

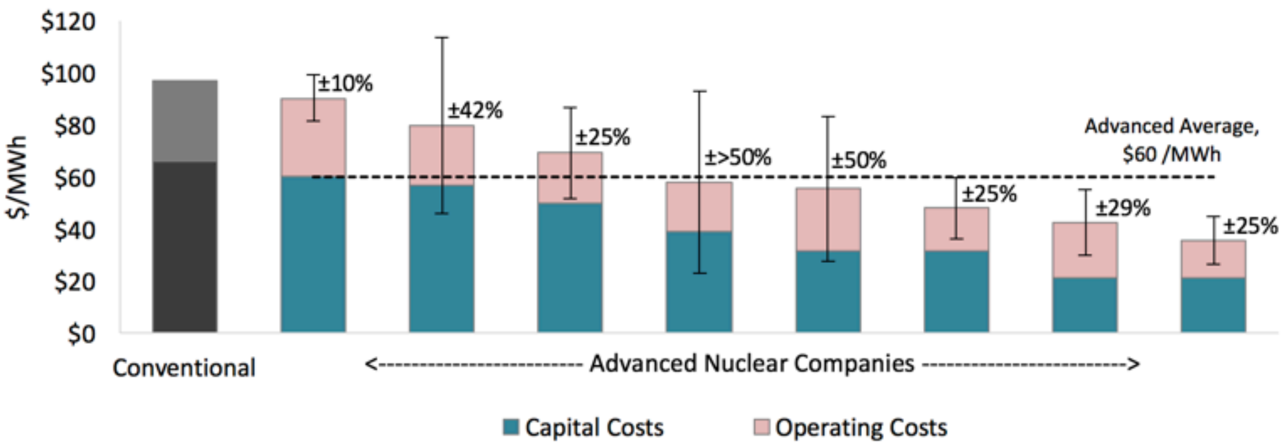
Note: All costs are expressed in 2016 dollars. Error bars reflect companies' self-reported confidence bounds.

As shown in the figure, operating costs consist of O&M costs, fuel costs, and financing during operation. Several companies expect to achieve large reductions in O&M costs largely due to lower staffing requirements. Companies reporting lower fuel costs cite fundamental differences in their fuel cycles or efficiencies.

Levelized Cost of Electricity

Figure 7 shows levelized cost of electricity (LCOE) for the conventional nuclear benchmark and participating advanced nuclear companies. The average LCOE for the companies surveyed is $60/MWh, a reduction of $37/MWh from the conventional nuclear LCOE of $97/MWh. The range of LCOE values across the participating companies reflects their specific combinations of design and delivery innovations (discussed in section 4).

Figure 7. Levelized Cost of Electricity Results



Source: EON analysis of conventional and advanced nuclear cost information as explained in text.

Note: All costs are expressed in 2016 dollars. Error bars reflect companies' self-reported confidence bounds.

LCOE represents the cost per MWh for full recovery of both capital and operating costs.[7] The capital recovery factor (CRF) spreads capital costs over multiple years based on a formula involving capitalization period and discount rate. EON assumed a capitalization period of 25 years and discount rate[8] of 7 percent to calculate the CRF consistently for all companies. These parameters for the CRF calculation are hypothetical values within the range of possible assumptions.[9] The capacity factor (CF) is assumed to be 95 percent for all companies.

EON's calculation of LCOE is a simplified formula and does not represent the power price that advanced nuclear companies would necessarily charge. The formula neglects year-by-year variations in operating costs, tax expenses (which depend on the tax rate and depreciation schedule in the relevant jurisdiction), corporate overhead (if additional to plant O&M), and other factors requiring additional assumptions. Actual power prices can differ from LCOE because of factors related to specific companies, projects, and markets (e.g., cost-of-service pricing in traditionally regulated markets versus competitive pricing in restructured markets).

7. EON used the following LCOE formula (from NREL 2017): LCOE = {(Total Capital Cost per kW * CRF * 1,000) / (8,760 * CF)} + Total Operating Cost per MWh.

8. Capital Recovery Factor (CRF) = {r * (1 + r)^n} / {[(1 + r)^n] - 1}, where n is the capitalization period and r is the discount rate.

9. EON used a hypothetical interest rate of 7 percent for calculating financing during construction, which captures compounded interest at a rate reflecting repayment of debt capital. To calculate LCOE, a 7 percent discount rate for levelizing total CAPEX was used, which reflects the return of capital (and return on capital) to debt and equity funders. This hypothetical discount rate is a coarse weighted average cost of capital, and does not reflect specific assumptions on the ratio of debt to equity or their respective required returns. Different interest and discount rates will result in different LCOE values.

3. STUDY METHODOLOGY

EON Model

To facilitate the preparation and presentation of cost estimates in a comparable and credible manner, EON developed a standardized cost model that includes default costs based on studies conducted by national nuclear laboratories. The Microsoft Excel–based model includes line-item costing for an entire nuclear plant and allows companies to declare where various cost-reduction strategies are expected to change their overall costs from default values.

Nth-of-a-Kind Cost Estimates

While acknowledging that each company must design and build a FOAK (first-of-a-kind) commercial plant, this study focuses on anticipated NOAK plant costs because they better reflect the eventual market competitiveness of the product, and that end-point will guide companies' reactor and plant design decisions. It is important to note that focusing on NOAK plant costs excludes the significant cost and time related to reactor licensing. It also disregards any issues related to "first-in-a-country" projects (e.g., potentially prolonged reactor or site-licensing process). Nevertheless, NOAK costs are the most useful metric for investors and policymakers. The following provides detail on the EON model's overall framework and key features.

The Generation IV International Forum

The Gen IV International Forum is an international cooperative consisting of 14 countries with the most active nuclear programs. It was established to carry out the research and development needed to determine the feasibility and performance capabilities of the next generation of nuclear energy systems. In 2007, it developed a standardized cost estimating protocol to provide decision makers with a credible basis to assess, compare, and eventually select future nuclear energy systems, taking into account a robust evaluation of their economic viability. EON used the Gen IV cost accounting system to build a flexible and user-friendly interface allowing start-up companies to input and validate the completeness of their costs.

Gen IV Accounting Protocol

To ensure that reported costs are adequately inclusive and easily compared to other materials, EON's cost model follows the cost accounting protocols set forth by the Generation IV International Forum. The Gen IV International Forum developed formalized cost categories to account for all capital and operating costs over time. This accounting system follows the U.S. Department of Energy's Energy Economic Data Base (EEDB) and a similar system developed by the International Atomic Energy Agency (IAEA). The accounting system disaggregates plant costs into nine different one-digit cost categories. These one-digit categories are further divided into more granular, two-digit and three-digit level costs. Using this accounting method ensures that all costs are considered. A representative hierarchy of Gen IV cost categories is shown in figure 8.

The Gen IV framework includes contingency cost accounts for each single-digit component; EON's model excludes contingency costs and instead asks companies to provide their best estimates for specific cost components and their confidence bounds around their cost estimates.

Appendix A provides an overview of the nine one-digit cost categories and appendix C describes the two-digit cost categories in detail.

Figure 8. Cost Categories in Gen IV Accounting Framework and EON Model

One-Digit Cost Categories

Code	Category
10s	Preconstruction Costs
20s	Direct Construction Costs
30s	Indirect Services Costs
40s	Owner's Costs
50s	Supplementary Costs
60s	Financing During Construction
70s	Operation and Maintenance (O&M) Costs
80s	Fuel Costs
90s	Financing During Operation

Two-Digit Cost Category Examples

Code	Category
21	Structures and Improvements
22	Reactor Equipment
23	Turbine Generator Equipment
24	Electrical Equipment
25	Heat Rejection System
26	Miscellaneous Equipment
27	Special Materials
28	Simulator

Three-Digit Cost Category Examples

Code	Category
221	Reactor Equipment
222	Main Heat Transport System
223	Safety Systems
224	Radioactive Waste Processing Systems
225	Fuel Handling Systems
226	Other Reactor Plant Equipment
227	Reactor Instrumentation and Control (I&C)
228	Reactor Plant Miscellaneous Items

Default Values from Prior Studies

EON populated each line-item cost with a default value. This served two purposes. First, it provided companies with reference values to ensure that each category included a vetted cost estimate. Second, it provided a baseline to which expected cost savings could be compared. Default values were sourced from cost studies of NOAK nuclear plants with conventional delivery assumptions conducted by Oak Ridge National Laboratory, Idaho National Laboratory, and the Generation IV International Forum, as discussed in appendix C. Cost figures from prior studies were inflated to 2016 dollars using the U.S. Consumer Price Index.[10]

For a relatively minor number of cost categories (listed in appendix C), the EON team could not find authoritative public information from which to develop default values. We viewed these categories as comparatively unique to each company and plant design. Therefore, we assumed relatively low costs for these categories and invited companies to enter their own estimates.

10. A more detailed inflation analysis could use different inflation factors based on historical price trends for specific cost components, such as nuclear equipment, turbine equipment, buildings, construction labor, concrete, and steel. Sources of construction price inflation include the Engineering News Record and R. S. Means.

Key Cost Driver Inputs

The cost categories within the Gen IV framework (which also underlie the EON model) reflect conventional approaches to nuclear construction, operation, and project financing. They are not designed to capture the innovative design and delivery strategies outlined in this report. Consequently, EON added additional functions to the model to reflect some of these innovations—specifically, the ability to define both the estimated level of plant design standardization and years for plant construction.

Standardization in plant design. EON's model allows users to define a "level of standardization" for plant design (up to 75 percent), which proportionately reduces the indirect services costs (the 30s cost category). The degree of plant design standardization reduces engineering, project management, and other indirect services costs, as discussed in appendix C.

Construction duration. The application of modular construction techniques, especially those practiced in large factories and shipyards, can dramatically reduce project lead times and reduce overall budgets. The default value for nuclear plant construction is seven years (based roughly on current U.S. PWR projects), which includes two years for preconstruction followed by five years for the main construction, testing, and commissioning. The EON model allows advanced nuclear companies to enter their own anticipated schedule. For total construction times less than seven years, cost reductions affect financing during construction (the 60s cost category).

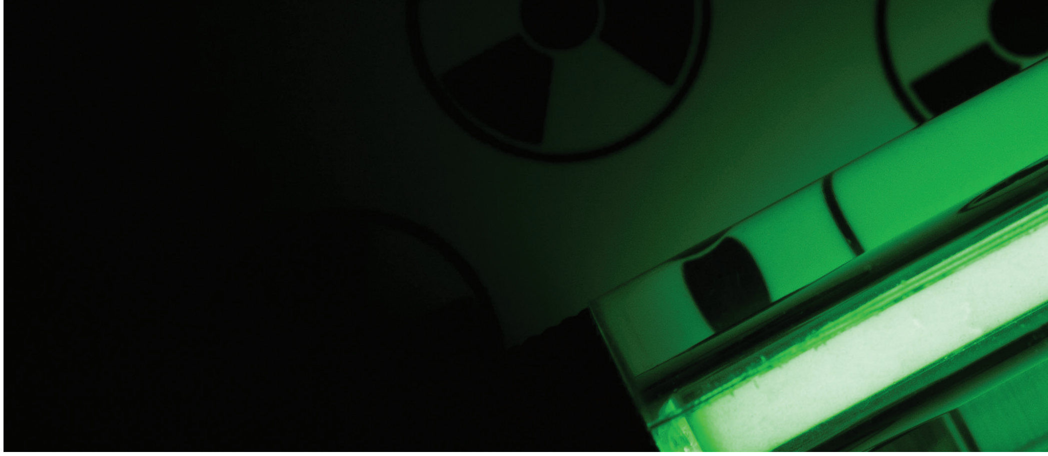
Line-Item "Adjustment Multipliers"

As expected, a given company's internal line-item costs sometimes differ from the default values in the model. Instead of having companies enter each value individually, EON required that they modify an "adjustment multiplier"—a number that, when multiplied by the default value, equals the company's internal estimate. (For example, if a company's internal estimates match the default value, it has an adjustment multiplier of 1. An adjustment multiplier of 2 means the company's internal cost estimates are double the default value, and if it is 0.5, the internal costs are half of the default value.) The purpose of this approach was to put the onus on the companies to adjust values from a fully populated cost model, ensuring that all costs were reported and allowing companies to leave in default values where necessary. When an adjustment multiplier was modified, users were asked to provide a rationale for the adjustment, as shown in figure 9.

Figure 9. Example of EON Model Interface with Adjustment Multipliers

		Headcount for Company's Plant Size (1100 MW)					
				Your Company Name			
	Take-Home Salary	PWR	Generic MSR	Adjustment Multiplier	Adjusted Value		Explanatory not Please describe left
Plant Manager's Office							
Plant Manager	$210,000	1	1	1.00	1		
Assistant manager	$147,000	1	1	1.00	1		
Public relations	$92,000	2	1	1.00	1		
Environmental control	$92,000	2	1	1.00	1		
Quality assurance	$107,000	6	3	1.33	4	Add note->	
Training	$103,000	48	1	1.00	1		
Safety and fire protection eng.	$86,000	7	2	1.00	2		
Administrative services	$57,000	80	14	0.80	11	Add note->	
Fire brigade	$50,000	27	14	1.00	14		
Security	$50,000	126	69	1.20	83	Add note->	
Subtotal		300	**108**		120		

Note: Example relates to a subset of cost components for O&M costs (70s cost category).



The EON model's mechanisms for entering cost information by single-digit cost category are shown in table 3.

Table 3. Cost Input Mechanisms in EON Model by Cost Category

Code	Category	Cost Input Mechanisms
10s	Preconstruction Costs	Line-item adjustment multipliers
20s	Direct Construction Costs	Line-item adjustment multipliers
30s	Indirect Services Costs	Design standardization reduction factor and line-item adjustment multipliers
40s	Owner's Costs	Line-item adjustment multipliers
50s	Supplementary Costs	Line-item adjustment multipliers
60s	Financing During Construction	Construction duration for calculating interest
70s	O&M Costs	Line-item adjustment multipliers
80s	Fuel Costs	User-defined values (or defaults)
90s	Financing During Operation	Line-item adjustment multipliers

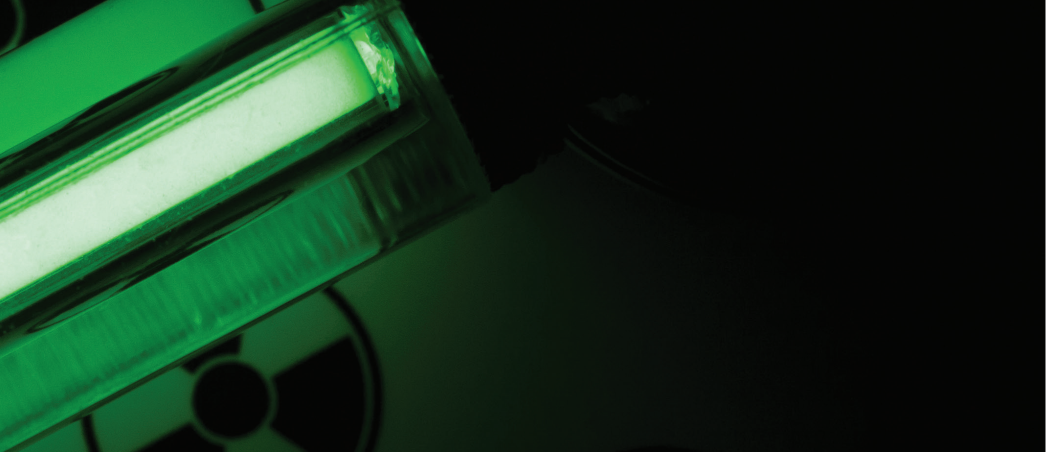
Data Review

EON assessed the completeness of information provided by the companies surveyed and identified any assumptions that appeared implausible or lacked rationale. In several cases, companies provided additional information or clarification as needed to explain the rationales for their estimates.

A shortcoming of this process was that the study scope did not allow for direct follow-up with the third-party engineering firms (e.g., Burns and Roe or Atkins) that provided the basis for certain cost estimates for select companies. The involved engineering firms were highly reputable and had deep nuclear construction experience, but the scope of work did not permit an independent verification of the cost estimates produced by these firms.

Level of Confidence

Companies were requested to apply confidence bounds in the model to 15 categories of direct construction and indirect services costs as well as the seven other single-digit cost categories. EON applied error bars to all reported costs based on these confidence bounds. This was an unavoidably subjective measure and was intended to prompt the study's staff to engage in a degree of self-scrutiny. Summaries of confidence levels are presented above with other study results.



Company Preparedness and Strategies

Company Preparedness with Cost Information

Each participating company had a working cost estimate for its plant. Although the depth and breadth of these analyses differed in many respects, each company was adequately prepared to participate in the study and found the cost categories and calculation methodologies to be familiar. Several companies had experienced cost analysts on staff.

Some companies simply entered their preexisting cost estimates into the model for submission, while others needed to reassess certain cost components. Moltex Energy, Transatomic Power, and X-energy were able to enter their costs into the EON model at the most detailed level requested. Other companies either provided information for EON to translate into the model or had plant delivery models wherein costs did not align well with the conventional nuclear cost of accounts. In the latter case, companies provided relatively detailed information about anticipated capital and operating costs, but it was not practical to allocate these costs among the provided accounts due to the uniqueness of plant designs and/or business approach.

Cost preparedness relates to two main factors: (1) design preparedness; and (2) cost preparedness for the given design. The most prepared companies had developed very detailed designs over many years and performed thorough cost analyses for their designs. The least prepared companies had less developed designs and cost analyses. Study participants fell along a spectrum in each dimension; some have spent many years on plant design, allocated staff to cost assessments, and prepared thorough estimates based on thousands of plant items with individual pricing parameters from vendors. Other companies have had less opportunity to develop that level of design detail, and used prior cost studies to guide certain components of their cost estimates.

Company Strategies for Cost Reduction

Companies provided a range of justifications for why they expect their approach to cost less than PWRs or the default costs provided for their advanced reactor type. The most common rationales for anticipated cost reductions were plant design standardization and reduction in construction duration.[11] Companies explained line-item deviations from the PWR benchmark or reference advanced reactor costs in various ways. Often, anticipated cost reductions were based on the fact that the plant design did not need to include certain components specified in the Gen IV/EON accounting framework, or did not need them at the same scale as a PWR.

For example, some companies do not need emergency feed pump buildings (cost code 218) because of their passive safety systems, or they need less plant equipment (cost code 226) because of the integrated nature of their design (as discussed for generic advanced reactor

11. Reducing construction duration is believed to be the consequence of completing designs prior to starting construction, replacing on-site construction with off-site manufacturing to the extent possible, and/or using simpler designs and less material, thus reducing construction risk (i.e., the potential for construction oversights and missteps) that may otherwise lead to schedule exceedance.

types in section 4). Many companies indicated that they needed less staff for certain O&M (70s) categories due to the inherent safety of the plant design.[12] Many of the lower line-item costs were justified by third-party EPC (engineering, procurement, and construction) studies or vendor bids. As discussed above, EON did not independently verify EPC studies or bids.

Limits of This Analysis

It should be noted that EON's model considered only electricity production from nuclear facilities, and calculated costs per MWh as a rough approximation of necessary electricity prices for full cost recovery on a levelized basis. Some reactor designs could produce more than electricity. For example, high-temperature gas reactors could be used to produce hydrogen (DOE 2006, INL 2012). Advanced reactors could also produce steam for district heating[13] and desalination services. Evaluating the potential economics of these alternative products could be valuable.

There are several areas where the calculations presented here could be further refined. For example, the LCOE calculation could be expanded by integrating inputs on year-by-year expenditures, tax rates, depreciation schedules, interest/discount rates, and other related parameters. Possible templates for more sophisticated financial analyses of nuclear power are suggested by MIT (2003, 2009).

Additional refinements could also include:

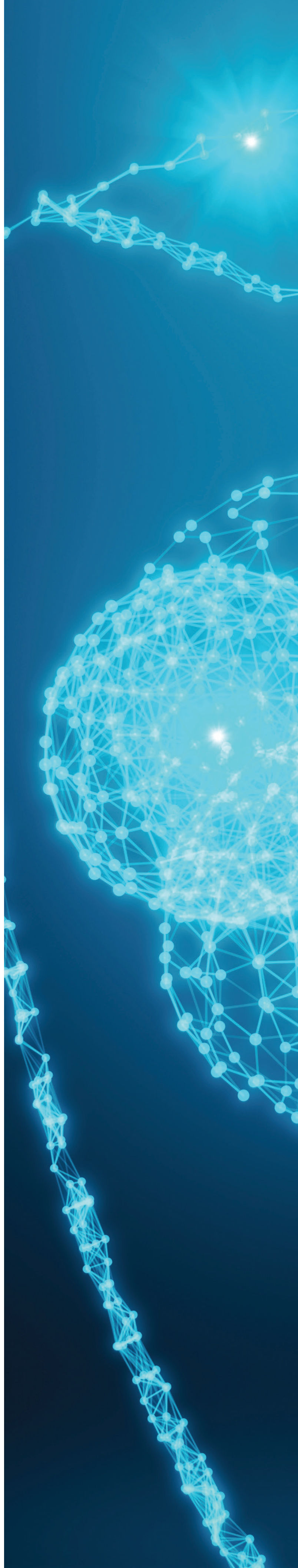
- More depth on the fuel cycle, with details on front-end and back-end cost drivers (as in the Gen IV spreadsheet model)
- Technology readiness level assessment for unproven plant design components
- Parameters to evolve from FOAK to NOAK plant estimates
- Inputs for different geographic assumptions, such as country-specific labor rates and commodity prices relevant to advanced nuclear construction or off-site manufacturing

Certainty Levels for Advanced Nuclear Cost Estimates

As noted, EON's model asked participating companies to specify their certainty level for cost estimates. Companies were given the option of choosing from among predefined certainty bands, or if no band was relevant, they were allowed to enter their information in an alternative format.

Companies that prepared detailed designs and performed thorough cost analyses using vendor price quotes, EPC studies, or actual cost data for comparable projects rated their confidence level as high (i.e., a confidence level "within 10 percent" or better) for the related cost components. Companies with a weaker basis for their estimates set lower confidence bounds.

EON's model does not calculate an overall uncertainty value for each reactor concept, but general conclusions from the certainty cells can be drawn. Companies that express high confidence in their estimates of the costliest components are likely to have the highest



12. O&M staffing costs also depend on whether the site hosts multiple units or the utility owns multiple plants.

13. District heating in this context describes the delivery of waste heat produced during electricity generation to serve distributed commercial and residential heating requirements.

certainty about total plant cost, even if some low-cost components have low certainty. Some costs for these plants are uncertain, but the costs for many components (turbine generators, control centers, balance of plant expenses, etc.) are well known from existing plants.

Using this methodology, EON developed approximate overall certainty levels for the participating companies. Of the eight companies, two have high certainty in their total cost estimates, three have medium certainty, and three have low certainty. Some of the companies with high overall certainty have significantly lower total capital costs than PWRs.

Realistic Considerations That May Influence Cost

Naturally, there are inherent limitations of a costing exercise for early-stage designs, and one can anticipate several reasons why final NOAK costs could deviate from these estimates. These cost estimates are not presented as definitive; they merely reflect the best available information. Projected costs also reflect the strategies that companies are pursuing to avoid the pitfalls that have undermined the economics of conventional nuclear power in the United States and Europe. Below is a list of uncertainties that are likely to influence the actual costs of advanced nuclear plants.

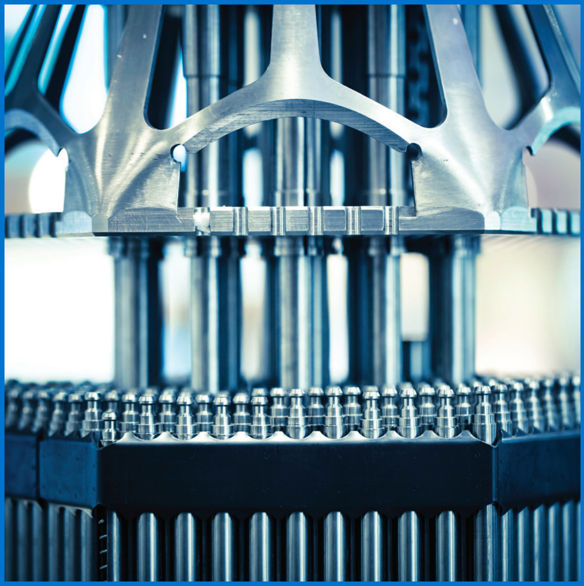
- Most companies are basing their cost estimates on preconceptual or conceptual reactor and plant designs. These are likely to evolve during the reactor and plant licensing processes—as well as after construction of their FOAK plant. RAND (1979) concludes that cost estimates for FOAK power projects in early design phases routinely underestimate ultimate capital costs. This study, by contrast, presents projected NOAK costs, and does not reflect the costs of licensing the reactor, testing specific materials or components, building a commercial-scale demonstration reactor, engaging in business development activities, or developing manufacturing facilities. While some costs may rise as designs evolve, many companies believe that the remaining design window also offers opportunities for further cost reductions.

- There is inherent and significant uncertainty in projecting NOAK costs from a group of companies that have not yet built a single commercial-scale demonstration reactor, let alone a first commercial plant. Without a commercial-scale plant as a reference, it is difficult to reliably estimate the costs of building out the manufacturing capacity needed to achieve the NOAK costs being reported; many questions still remain unanswered—what scale of investments will be needed to launch the supply chain; what type of capacity building will be needed for the supply chain, and so forth.

- Companies are developing simpler designs that can be built or assembled much faster than conventional plants. That said, having to depend on large EPCs during construction (or on-site assembly) introduces a substantial degree of cost uncertainty. The number and scope of change orders can rise dramatically depending on the level of design completion. Assuming factory- or shipyard-based manufacturing (for components, assemblies, or modules), final designs will need to be nearly complete. This may help offset any unforeseen deviations in cost due to design changes or setbacks in construction execution.

- Many of the companies are using well-established, qualified fuels (e.g., uranium oxide fuel rods, TRISO pebbles), but some will use fuels that require further testing to be qualified, and some of the fuels may be more difficult and expensive to source and fabricate than those currently in use. There are necessarily uncertainties in the cost estimates for these fuels.

4. ADVANCED NUCLEAR'S DESIGN AND DELIVERY INNOVATIONS



Advanced nuclear companies use several innovations that differ from conventional nuclear power. This section briefly introduces the cost context for conventional nuclear plants and then presents a variety of innovative ways in which advanced reactors may enable savings in both plant construction and operation.

Context: The Cost of Conventional Nuclear

Table 4 shows generic capital cost estimates for a conventional nuclear power plant in the United States. The estimated cost of power from this table ($6,755/kW) was used as a benchmark for conventional nuclear costs for the purposes of this report. The detailed cost-accounting reflects government studies, primarily from Oak Ridge National Laboratory (ORNL).

We chose this as a benchmark as opposed to using estimates of nuclear projects currently under construction in the United States. The projects at Vogtle (units 3 and 4) and V.C. Summer (units 2 and 3) are FOAK plants in the United States, and their full cost is still in flux and not publicly available. Our benchmark estimate falls in between the current estimates of these two projects.[14]

Table 4. Generic Capital Cost Estimates for U.S. Conventional Nuclear

Category	$/kW	% of Total
Direct construction costs		
Equipment	$990/kW	15
Labor	$941/kW	14
Materials	$287/kW	4
DIRECT CONSTRUCTION SUBTOTAL	**$2,218/KW**	**33**
Indirect services costs		
Off-site engineering and design	$860/kW	13
On-site project management	$695/kW	10
Other on- and off-site indirect services	$916/kW	14
Indirect services subtotal	$2,470/kW	37
DIRECT AND INDIRECT CONSTRUCTION SUBTOTAL	**$4,688/KW**	**70**
Preconstruction costs	$131/kW	2
Owner's costs	$703/kW	10
Supplementary costs	$78/kW	1
Financing during construction	$1,155/kW	17
TOTAL CAPITAL COSTS	**$6,755/KW**	

Source: ORNL (1986) and EON calculations (as described in appendix C).

Note: Costs reflect the median experience for nuclear power plant construction.

14. Regulatory filings by the utility owners of the Summer and Vogtle nuclear projects indicate that, upon approval of the projects in 2009, the forecasted capital costs were $5,137/kW for Summer and $5,929/kW for Vogtle (based on total costs cited in the sources, ownership percentages for the respective utilities, reactor capacity for each AP1000 unit, and nominal dollars reflecting expenditures across multiple years). See SCE&G (2017, 4) and Georgia Power (2017, 7). As of December 2016, the costs had risen to $6,247/kW for Summer and $7,586/kW for Vogtle. At the time of this writing, the companies are developing new cost estimates, in response to the bankruptcy of Westinghouse, but these are not yet available.

As shown in table 4, direct construction costs represent only about 33 percent of the total plant costs. Direct construction costs include the plant hardware (nuclear reactor, buildings, power conversion equipment, etc.) as well as labor to build the plant. The largest component of plant costs is indirect services. This category includes engineering during construction, on-site project management, field indirect costs (temporary buildings, equipment rental, laydown areas and warehousing, etc.), and a host of other costs. The third-largest cost driver is financing during construction, which can escalate dramatically if construction is delayed.

Not all advanced reactor companies are focused on reducing construction costs (some companies expect costs similar to or higher than those for PWR; see section 4), but all companies surveyed expect to reduce overall costs by reducing the cost of indirect services. Many also expect to reduce construction financing costs by enabling shorter construction periods. To achieve these savings, companies are pursuing a multiplicity of design and construction strategies, which are outlined below.

Design Considerations for Conventional Nuclear Reactors

A significant part of the design basis for a conventional nuclear plant is the need to minimize and control accident-related risks. Plant design, construction, and operation require large numbers of high-skilled professionals to ensure safety at every point. These safety measures guide the costs for engineering, equipment, materials, labor, supervision, inspection, and operations. Materials such as nuclear-grade concrete and steel must meet rigorous standards for reliable performance in extreme scenarios. Operators must constantly monitor fouling, corrosion, and equipment degradation. Security is also a large cost component of plant operation and includes averting site attacks and preventing theft of nuclear materials.[15]

Safety Enhancements of Advanced Nuclear

Advanced nuclear plants require the same high levels of expertise and oversight during their construction and operation as conventional plants, but advanced reactors have simpler and more reliable safety systems and require relatively less safety-related oversight, due to their neutronics and thermal-fluidic properties. This enables the possibility of providing a greater level of safety at lower cost.

Fundamental reactor and plant design choices can (1) reduce susceptibility to hazards, (2) lessen the consequences of hazards, (3) reduce the required response, and (4) greatly improve the recovery from hazards. Consequently, these choices could reduce the need for complex engineering designed to control hazards.

15. Reducing security costs is largely driven by plant design, not technology (i.e., conventional versus advanced reactors). As highlighted in Conway (2016), changes in plant design and layout can make it possible to dramatically reduce security costs while maintaining adequate security.

Overview of Reactor Designs

What follows is a brief overview of the advanced nuclear designs under consideration in this study. Each reactor type has implications for potential construction and operating cost reductions relative to conventional nuclear.

Molten Salt Reactors

Molten salt reactors (MSRs) use molten salts as fuel and coolant. The salts flow through a low-pressure reactor core and heat exchanger, with one or more salt loops as an interface with a power generation system. Using molten salt as a fuel rules out uncontrolled chain reactions, because any temperature rise in the reactor core would increase the distance between fissile isotopes in the molten salt, thus applying an automatic brake to the reaction. MSR designs can also incorporate a frozen drain plug that would automatically melt in case of excessive overheating; this would quickly remove fuel from the reactor core.

The combination of inherent safety and low pressure reduces the number and complexity of necessary parts in MSR plants. There is much less need for backup systems. Partially counteracting these savings, however, are special equipment requirements for molten salts. High-temperature molten salt circulation pumps must supply large flow rates throughout the plant at lower pressures than PWRs. Moreover, the salt and fuel mixture must be maintained at sufficiently high temperature to avoid solidifying in the plant piping, and corrosion caused by the salt constituents must be minimized.

Three MSRs have been successfully designed, built, operated, and tested. The first of these was the 2.5 MWt Aircraft Reactor Experiment at ORNL, which operated for 1,000 continuous hours in 1954. This led to the development of a small-scale MSR in 1957 that ran for only a few weeks.[16] The most well-known MSR was the 7.4 MWth Molten-Salt Reactor Experiment (MSRE), which successfully ran at ORNL from 1965 to 1969. There have been many subsequent MSR designs, and China is now constructing a 5 MW thorium-breeding MSR with a 2020 target date for operation.

High-Temperature Gas Reactors

High-temperature gas reactors (HTGRs) have much higher reactor outlet temperatures than PWRs and use helium as the coolant. HTGRs are classified into two subdivisions by their solid fuel geometry. In prismatic block reactors, hexagonal graphite blocks are stacked within the pressure vessel. In pebble bed reactors, small spheres containing fuel descend slowly through the reactor core. The fuel particles are coated with isotropic materials in three layers (TRISO). Coated fuel particles greatly enhance safety at HTGRs because they protect against radioactive releases and core meltdown. Several HTGR concepts are suitable for underground installation, which boosts their safety profile even further.

The higher operating temperatures of HTGRs improve overall plant efficiency relative to PWRs. Since helium is an inert gas that will not liquefy (or solidify) and will not cause corrosion in plant piping, the material-handling aspects of HTGRs are straightforward. Unlike some other advanced reactor types, however, HTGRs operate at high pressures. The higher operating temperatures of HTGRs also provide opportunities for hydrogen production, steam for district heating, process heat, desalination services, or other applications.

16. The Pratt and Whitney Aircraft Reactor-1 (PWAR-1) operated for about three weeks in February 1957 to verify the theoretically predicted nuclear properties of the reactor. The research intent of the reactor was met and it was subsequently disassembled.

Several commercial-scale HTGR demonstration plants have been built. The longest successfully operating plant is Germany's 15 MW AVR, which ran for more than 21 years (1966–1988). A 330 MW HTGR operated at Fort St. Vrain in the United States for 10 years (1979–1989), and China is completing construction of a 210 MW pebble bed reactor, which is expected to start commercial operation in late 2017.

Sodium-Cooled Fast Reactors

Sodium-cooled fast reactors (SFRs) are a type of liquid metal–cooled fast reactor that uses liquefied sodium as coolant.[17] Sodium has a relatively low melting point compared to other possible metals (making it easier to use); the coolant loop operates at low pressure, and does not cause corrosion in appropriate alloys of pipe. Sodium, however, reacts violently with water and air, necessitating tight encapsulation of sodium loops in the plant.

In general, sodium-cooled reactors have high temperatures and thermal efficiencies. The high temperature differential of the core also allows for more passive safety systems driven by the natural circulation for decay heat removal. Their high power density implies lower equipment and material requirements per MW of plant output. Indeed, their compact design allows for modularity at the system and possibly the entire plant level.

SFRs operate in the "fast" end of the neutron spectrum without a moderator. Fast breeder reactors are self-sufficient in their fuel needs after reaching a steady state. Upon reaching criticality, the reactor can turn highly abundant (and relatively inexpensive) isotopes such as 238U and 232Th into relatively scarce, fissile isotopes (e.g., 233U, 239Pu, etc.), which are then burned as fuel. Fast reactors also have the unique ability to transform and/or burn nuclear waste from power production or weapons programs. This turns a liability into a fuel feedstock and prevents the need to produce and store large quantities of spent nuclear fuel.

There have been approximately 20 SFRs designed and built across the globe, most of which have been experimental reactors. Arguably the most famous SFR operated in the United States was the Experimental Breeder Reactor II, which achieved criticality in 1965 and operated for 30 years at Argonne National Laboratory–West (which became Idaho National Laboratory in 2005). The largest SFR ever built (800 MW) was completed in Russia in August 2016, and India is expected to start operations of a 500 MW SFR in late 2017.

Advanced Pressurized Water Reactors

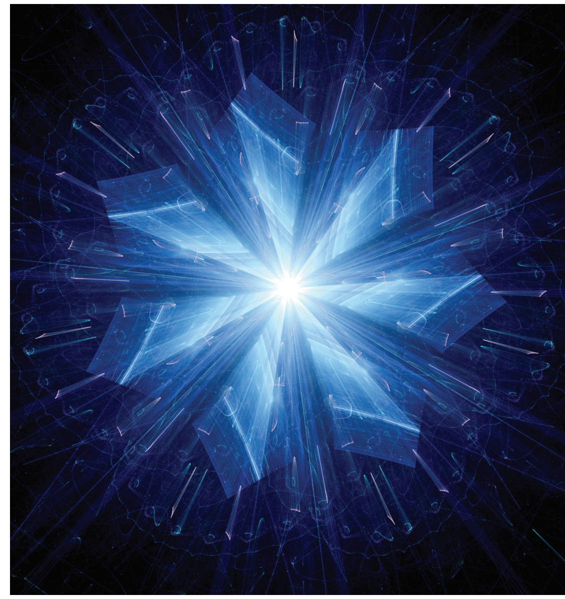
Advanced PWRs embody major design changes relative to conventional PWRs and include advanced passive safety systems and extensive simplifications to enhance plant construction, operation, and maintenance. Some advanced PWR designs are highly modular and are intended for manufacturing. They use many fewer pumps and systems than conventional PWRs, are easily transportable, and can be installed underground.

Delivery Issues with Conventional Nuclear Power

Fabrication methods for delivering conventional nuclear power projects, specifically in the United States and Europe, also contribute toward their high construction costs.[18] In the conventional delivery model, plant designs typically differ from one site to the next, even for plants using the same reactor model. Plant designs are highly specific to various physical, seismic, and infrastructure considerations, which can raise costs for project-specific engineering, construction management, and inspection. Costs are also high because conventional nuclear projects require on-site assembly and installation of complex systems.

17. Another type of liquid metal–cooled fast reactor uses lead as a coolant, which has several important trade-offs with sodium. As this study does not include any companies developing lead-cooled fast reactors, we omit a description.

Typically, construction is begun before the plant design is completed, in an effort to compress the project schedule. In practice, however, delays and cost overruns are likely due to a combination of real-time design modifications, corresponding change orders, and the involvement of contractors and subcontractors with varying levels of experience and standards. Change orders that occur because of amended plant designs can inflate materials costs and prolong construction, significantly increasing financing costs.



Advanced reactor companies are developing plant designs in ways intended to avoid the nature and scale of risks associated with these highly customized, site-built projects. This includes high levels of modularization and standardization in plant designs, as well as exploring new manufacturing strategies and business models to limit the risk of cascading schedule delays and the amount of up-front capital needed.

Innovations in the Delivery of Advanced Nuclear Technologies

There are several innovative strategies that can simplify and streamline construction of advanced reactors; most companies are pursuing some subset of these strategies. Below we review five common strategies.

1. Simpler and Standardized Designs

Advanced nuclear plants are designed to be mechanically simpler than conventional plants. They include more passive safety systems, more opportunities to use natural circulation, and have fewer pumps, valves, and other components characteristic of older, "actively safe" nuclear plants. They also require notably less design detailing. Simpler designs reduce indirect services costs (specifically on- and off-site engineering design services and construction supervision), and should theoretically reduce the scope of design customization needed at each site.

Standardization is embedded in the design philosophy of advanced nuclear companies and offers clear cost-reduction opportunities. Having blueprints that do not significantly change from plant to plant can lower indirect services costs, which exceed $2 billion for each generic 1,000 MW PWR (see table 4). Standardization drives cost savings by reducing the need for site-specific engineering, in turn reducing the quantity and scope of change orders and hence lowering labor costs, enabling faster construction, and allowing for greater competition within the supply chain (and presumably leading to more prepared vendors). These benefits would be especially evident when there are multiple orders. Reducing the risk of scheduling delays and budget overruns should improve financing terms and lower interest accrued during construction. While all advanced nuclear plants will require some degree of customization due to site characteristics (which drive considerations such as cooling-water intake), the philosophical shift from plant design to product design has the potential to reduce costs in a variety of ways.

Standardization has also been a key to the success of Korean, Japanese, and Chinese nuclear plant developers. Because they are constructing projects with greater frequency, they are also able to retain the skills and experience they acquire (something that has been difficult in the United States and Europe due to a steep drop in new plant construction since the 1980s).

18. Nuclear plants constructed by the Japanese, Koreans, and Chinese have not been affected by the types of delivery issues experienced in the United States and Europe. Their ability to deliver low-cost projects can be largely attributed to a combination of design standardization, modularization, low labor rates, non-U.S./European regulatory contexts, lower commodity and equipment prices, laborers with retained nuclear experience, and 24-hour/seven-day-a-week construction.

2. Factory/Shipyard Manufacturing

Apart from the plants being built by the Koreans, Chinese, and Japanese (Schneider and Froggatt. 2015), nuclear construction projects have required increasingly longer build times—particularly in the United States and Europe (Lovering, Yip, and Nordhaus 2016). There are several factors behind these prolonged construction times, including customized designs and components, highly site-specific engineering and design work, and different contractors with different levels of experience and standards.

Seeking to learn lessons from those experiences, several advanced nuclear companies are seeking ways to manufacture as much of the plant as possible in factories, rather than on-site. They are borrowing manufacturing models from other, highly productive sectors of the economy and designing plants so that components, systems, modules, or entire plants can be fabricated in dedicated factories or shipyards. This strategy offers the following advantages:

- **Faster delivery,** made possible because factories and shipyards routinely operate around tight schedules, are under constant pressure to innovate and improve productivity and quality, and are tested by the market more rigorously than nuclear construction projects under an EPC approach.

- **Earlier detection of defects and faults** than with stick-built construction.

- **Tight tracking of parts and status**, with barcodes, and/or RFID tags, throughout the facility (and possibly the broader supply chain).

- **Ongoing productivity and specialization improvements by dedicated teams**, which are located in the same place, perform the same task, and work on multiple orders.

- **Substantially greater opportunity to reduce sequential delay linkages**, since the delay will be the longest individual delay instead of the sum of all individual delays.

- **Reduced risk of schedule exceedance**, which consequently reduces the risk of budget exceedance and interest payments.

- **Reduced concurrent engineering and construction**, which reduces the possibility of change orders and associated engineering and vendor expenses.

The high productivity at a factory or shipyard, coupled with the other advantages listed above, can yield large reductions in plant construction costs.

3. Lower Materials Requirements

Some advanced nuclear companies are pursuing designs that reduce the amount of materials (concrete, steel, etc.) and/or substitute low-cost materials for some structural and protective applications. Achieving material reduction often requires focusing on simpler designs that reduce the necessary number of components, systems, and buildings. The result is both reduction of direct construction costs and the number of items to be designed, engineered, tested and certified (if necessary), licensed, and ultimately built. Any reduction in construction scope is likely to lower the corresponding indirect services costs (e.g., design services, construction supervision, equipment rental, temporary structures), and consequently, construction schedules and financing costs.

4. Modularization

Simpler designs for advanced nuclear concepts lend themselves well to modularization—that is, to the division of complex systems into constituent parts that are uniform, transferrable, separately manufactured, and easily handled. Modularization shifts the model for power plant construction from the conventional fabrication approach to mass production and rapid assembly. Another advantage of modularization is the easing (or elimination) of transportation constraints from the manufacturing point to the project site.

5. Alternatives to Engineering, Procurement, and Construction Model

Simplification, standardization, factory/shipyard-based manufacturing, and modularization reduce the scope of work for the EPC. Instead, a higher percentage of the plant capital expenditure (CAPEX) can be delivered in a near-finished state. Since the conventional EPC revenue model introduces incentives for complexity, one-off engineering work, change orders, and long construction schedules, alternatives to the EPC model can reduce costs in multiple areas.

Design Factors That Could Increase Advanced Nuclear Costs

While the features of advanced reactors introduce opportunities to reduce costs, there are also specific design and operating conditions that may add costs, including the following:

- Smaller power rating. Some companies are building smaller reactors to make manufacturing and installation easier. While doing so may support streamlined quality assurance or enable faster production, it diminishes the ability to leverage economies of scale.
- Lower power density. Some reactor types, notably HTGRs, have relatively low power density cores. This may raise the cost per MW as a result.
- Specialized processing. Some companies may require specialized chemical processing for fuels (e.g., for molten salt reactors) and/or complicated refueling processes.
- Multidecade fuel load. Some companies are developing reactors with large initial fuel loads that can last for decades. Although the longer fuel cycles allow these companies to reduce operating expenditures, they increase the total capital expenditure.

5. CONCLUSIONS

EON's model was designed to permit a standardized, apples-to-apples comparison of NOAK plant costs for a range of advanced nuclear technologies. Advanced nuclear companies are designing plants that could be highly cost competitive in energy markets driven purely by economics. Costs below $2,500/kW (as projected by two participants) would be transformative. Companies participating in this survey had more detailed costs than anticipated, and were able to provide a credible basis for their cost estimates.

There was no correlation between a given company's construction experience and its projected costs, which casts doubt upon the commonly held view that low costs are a consequence of incomplete scope or lack of experience.

Modularity and standardization are expected to benefit different companies in different ways. These factors would reduce overnight costs for some companies but not for others. Primarily, standardization reduces the level of engineering and supervision needed during construction, which would lower the cost of indirect services. It would also reduce construction risk (i.e., likelihood of delays), which could affect the total delivered cost.

This study is designed to help inform the investors and policymakers whose commitment will be necessary to sustain and accelerate industry progress. Companies have raised only a small fraction of the capital required to build a commercial-scale demonstration reactor. Financing such projects could require new types of investors and non traditional investment models. For an objective analysis, it is important to dispel misconceptions on costs and clarify how the advanced reactor companies expect to reach their targets and compete in the open market.

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APPENDIX A: NUCLEAR PLANT COST CATEGORIES

Cost categories for evaluating nuclear power plant economics have been formally defined by government agencies and nuclear associations over several decades. In this study, we use the international standard for comprehensive and standardized nuclear cost accounts set by the Generation IV International Forum. All cost accounts are classified as either (1) capital costs for up-front expenditures related to plant construction; or (2) operating costs measured for ongoing expenditures related to plant operation. Categories for capital costs and operating costs are explained below.

Capital Cost Categories	
Direct construction costs	These cost accounts comprise expenditures for equipment, labor, and materials to construct the nuclear power plant. The cost accounting framework encompasses all component systems of a nuclear power plant: (1) buildings; (2) reactor; (3) turbine generator; (4) electrical connections; (5) heat rejection; and (6) miscellaneous items.
Indirect services costs	These cost accounts comprise expenditures for services during plant construction, such as (1) engineering; (2) project supervision; (3) quality assurance; (4) testing; and (5) commissioning. Most indirect services costs reflect pay for technical professionals involved in design and delivery of the nuclear power plant. Note that indirect services costs relate to the specific power plant and not to designing and licensing a new nuclear reactor for general usage, which must be completed with the national regulatory authority before actual plant construction.
Preconstruction costs, owner's costs, and supplementary costs	Preconstruction costs include land acquisition, environmental studies, and plant permitting (separate from reactor licensing for general usage). Owner's costs include staff recruitment, training, housing, and salary-related costs. Supplementary costs include initial spare parts and two categories that may or may not be capitalized with the plant up-front costs: initial fuel core load and decommissioning.
Financing during construction	The most significant cost account in this category is interest during construction (IDC), which reflects compound interest on debt and equity capital applied to the plant project. IDC depends on the total amount for capitalized costs listed above, the cost of capital (discount rate), and construction timing in terms of expenditures by year and overall construction duration.

Operating Cost Categories	
Operation and maintenance (O&M) costs	The largest cost account within this category comprises on-site staff such as managers, technicians, compliance officers, safety monitors, fire brigades, and security personnel. The category also includes salary-related costs, utilities, supplies, insurance, and taxes.
Fuel costs	These cost accounts comprise fuel inputs to the nuclear power plant (front end of the fuel cycle) as well as reprocessing and storage of spent fuel (back end of the fuel cycle). Any special materials for plant operation, such as coolant needing replenishment, also go into this category.
Financing during operation	This category includes annual fees to the nuclear regulator as well as any cost contributions related to escalation and ongoing financing. In addition, this category can include annual lease payments if the plant financial scheme involves such an arrangement.

APPENDIX B: OPERATING COSTS FOR A NUCLEAR PLANT

Table B.1 shows generic operating cost estimates for a conventional power plant in the United States. The O&M and financing cost estimates shown are from ORNL (1987), which lists generic PWR values, with escalation to account for price inflation.[19] The fuel cost estimates come from Energy Information Administration (EIA 2017a) parameters for new power plants.

Table B.1. Generic Operating Cost Estimates for Conventional Nuclear

Category	$/MWh
O&M costs	$23/MWh
Fuel costs	$7/MWh
Financing during operation	$0.3/MWh
Total operating costs	$31/MWh

Source: ORNL 1987; EIA 2017; EON calculations (as described in appendix C).

The generic capital costs and generic operating costs are the main drivers of levelized total cost and necessary power price for nuclear plants. Using the LCOE formula and parameter assumptions discussed in section 4, and based on the capital costs given in table 1 and operating costs in table B.1, we calculate the LCOE for conventional nuclear at $97/MWh.

19. Escalation is calculated using the U.S Bureau of Labor Statistics Consumer Price Index (1987–2016).

APPENDIX C: COST CATEGORY DETAILS AND MODELING METHODOLOGY

The tables below describe the cost categories in the EON model, which were derived from the Gen IV International Forum's framework, as well as EON's sources and methodology for entering default values for conventional nuclear and generic advanced reactor types.

10: Preconstruction Costs

Code	Category	Description
11	Land and Land Rights	This account includes the purchase of new land for the reactor site and land needed for any co-located facilities such as dedicated fuel cycle facilities. Costs for acquisition of land rights should be included. This category does not include siting costs such as geotechnical work (account 211) or the preparation of environmental documentation (account 16). (This account is not in the IAEA account system but is included in EEDB account 20; the Energy Management Working Group (EMWG) decided to retain this scope in new account 11).
12	Site Permits	This account includes costs associated with obtaining all site-related permits for subsequent construction of the permanent plant.
13	Plant Licensing	This account includes costs associated with obtaining plant licenses for construction and operation of the plant.
14	Plant Permits	This account includes costs associated with obtaining all permits for construction and operation of the plant.
15	Plant Studies	This account includes costs associated with plant studies performed for the site or plant in support of construction and operation of the plant.
16	Plant Reports	This account includes costs associated with production of major reports, such as an environmental impact statement or the safety analysis report.
17	Other Preconstruction Costs	This account includes other costs that are incurred by the owner prior to start of construction and may include public awareness programs, site remediation work for plant licensing, etc.

Sources	• OECD Nuclear Energy Agency 2000. • Missouri House Bill No. 124, 96th General Assembly (2010). • Georgia Public Service Commission 2016. • U.S. Nuclear Regulatory Commission 1996.
Default Value Calculation Methodology	Default values for codes 11, 12, 13, and 16 were either directly sourced or based on costs cited in the sources listed above. For cost code 12, we estimated the cost of the early site permit based on what the Missouri government allows its resident utility, Ameren Missouri, to charge customers for such a study. In the absence of specific costs for all preconstruction reports (cost code 16), we found U.S. Nuclear Regulatory Commission estimates for the total man-hours needed for an environmental report and environmental impact statement (10,000 hours) and multiplied it by the commission's 2016 hourly rate ($265/hour); we assumed that the safety action report would cost approximately the same. Where necessary, all costs were brought up to 2016 dollars using the U.S. Bureau of Labor Statistics Consumer Price Index. Unique to the preconstruction cost category, we assumed that all costs were incurred irrespective of plant capacity (i.e., the cost of site acquisition is the same for a 500 MWe reactor and 1,500 MWe reactor). In the absence of verifiable cost information, we entered a placeholder value of $10 million for each of the following codes: 14, 15, 17, and 19.

20: Direct Construction Costs

Code	Category	Description
21	Structures and Improvements	This account covers costs for civil work and civil structures, mostly buildings, exclusive of those for the cooling towers.
22	Reactor Equipment	This category is most dependent on the reactor technology being considered, because the subaccount descriptions and costs depend heavily on what coolant is used and whether the subsystems are factory-produced or constructed on site. For today's light water reactors, the entire nuclear steam supply system (NSSS) can be purchased as a unit from a reactor vendor. The reactor manufacturer may have its own code of account (COA) structure for all the NSSS components. The list below attempts to be as generic as possible. The initial and reload fuel cores are not included here.
23	Turbine Generator Equipment	This category assumes that electricity is the primary product. The categories below apply mostly to a steam-driven turbine; however, similar categories would exist for gas-driven turbines. This account includes all process equipment and systems associated with the plant output. For other plant systems (e.g., water desalination, hydrogen production), appropriate coding is required to separate the plant into logical and significant plant systems.
24	Electrical Equipment	Accounts 21 through 23 all have interfaces with the power plant electrical service system and its associated equipment. This equipment is located both inside and outside the main reactor/balance-of-plant (BOP) buildings. (Note: The IAEA account system normally puts all instrumentation and control (I&C) costs in this account. The EMWG decided to retain I&C costs within the accounts that require I&C equipment, mainly accounts 227 and 236.)
25	Heat Rejection System	This account includes heat rejection equipment such as circulating water pumps, piping, valves, and cooling towers, which may be required even if the plant does not produce electricity. (This is account 26 in the original EEDB [ORNL 1988].)
26	Miscellaneous Equipment	This account covers items not in the categories above. (This is account 25 in the original EEDB.)
27	Special Materials	This account includes nonfuel items such as heavy water, other special coolants, and salts needed before start-up.
28	Simulator	This account includes the development of new simulators for training operators.

20: Direct Construction Costs (cont.)

Sources	• ORNL 1986 • ORNL 1980 • INL 2012
Default Value Calculation Methodology	Descriptions of the two-digit cost categories are given above; however, the model included 66 three-digit cost categories for direct construction costs. For each three-digit category, we provided default values for factory equipment costs, site labor hours, site labor cost, site material cost, and total cost. These were provided for both PWRs and the three generic advanced reactor types. We describe our methodology for arriving at the default values based on the cost studies listed above, as well as our assumptions for any modifications/ updates we chose to make to those default values. • PWR: The ORNL (1986) study presented PWR costs in terms of both a "best" and "median" industry cost experience. For the purposes of this study, we included only the median costs, as they more closely reflect the costs of plants built after the Chernobyl and Three Mile Island incidents. Costs were pulled from table 5-3 and values were brought from 1986 to 2016 dollars using a factor of 2.2 (calculated using annual rate increases in the U.S. Bureau of Labor Statistics Consumer Price Index). Values were converted from million dollars to dollars per kW using representative plant capacity in the source report (1,144 MWe). • Generic Reactor Types: o MSR: ORNL (1980) provided three-digit default MSR values in 1978 dollars, which we converted to 2016 dollars using a 3.7x inflator (based on the Consumer Price Index). We converted from million dollars to dollars per kW using the listed plant capacity in the ORNL report (1,000 MWe). We then broke out costs by factory equipment costs, site labor hours, site labor cost, and site material cost by calculating the ratio of equipment cost/labor hours/labor cost/site material cost to total direct construction cost for PWRs and applied the same ratio for MSRs. Labor costs were scaled to be consistent with the median PWR experience from ORNL (1986). o HTGR: The level of relative granularity in costs was the lowest for HTGRs. We referenced the INL's (2012) report (table 6) and inflated 2009 values to 2016 dollars using a factor of 1.1, and converted from million dollars to dollars per kW using the listed plant capacity in the report (600 MWe). Cost information was provided at the two-digit level, and we either did not disaggregate cost to three digits (e.g., category 21) or we applied a ratio of two-digit to three-digit costs found for PWRs. o SFRs: The values for SFRs were pulled from the ORNL (1986) study (inclusive of all three-digit costs); however, these values were for a FOAK reactor. To convert these to NOAK reactor costs, we scaled down direct and indirect services costs by 35 percent. This represented the midpoint of the 15–55 percent range provided in the INL (2014) report on FOAK-to-NOAK expected cost savings (see Bolden and Sabharwall [2014], 2). As with the PWR costs, values were inflated from 1986 to 2016 dollars using a factor of 2.2 and converted from million dollars to dollars per kW using the listed plant capacity in the report (1,311 MWe).

30: Indirect Services Cost

Code	Category	Description
31	Field Indirect Costs	This account includes cost of construction equipment rental or purchase, temporary buildings, shops, lay-down areas, parking areas, tools, supplies, consumables, utilities, temporary construction, warehousing, and other support services. Account 31 also includes • Temporary construction facilities, such as site offices, warehouses, shops, trailers, portable offices, portable restroom facilities, temporary worker housing, and tents • Tools and heavy equipment used by craft workers and rented equipment such as cranes, bulldozers, graders, and welders (equipment with values of less than $1,000 are typically categorized as tools) • Transport vehicles rented or allocated to the project, such as fuel trucks, flatbed trucks, large trucks, cement mixers, tanker trucks, official automobiles, buses, vans, and light trucks • Expendable supplies, consumables, and safety equipment • Utilities, office furnishings, office equipment, office supplies, radio communications, mail service, phone service, and construction insurance • Construction support services, temporary installations, warehousing, material handling, site cleanup, water delivery, road and parking area maintenance, weather protection and repairs, snow clearing, and maintenance of tools and equipment
32	Construction Supervision	This account covers the direct supervision of construction (craft-performed) activities by the construction contractors or of direct-hire craft labor by the architect/engineer (A/E) contractor. The costs of the craft laborers themselves are covered in the labor hours component of the direct cost in accounts 21 through 28 or in account 31. This account covers work done at the site in what are usually temporary or rented facilities. It includes nonmanual supervisory staff, such as field engineers and superintendents. Other nonmanual field staff are included with account 38 (PM/CM [program management/construction management] services on site).
33	Commissioning and Start-up Costs	This account includes costs incurred by the A/E, reactor vendor, other equipment vendors, and owner or owner's representative for start-up of the plant, including start-up procedure development, trial test-run services, and commissioning of materials, consumables, tools, and equipment.
34	Demonstration Test Run	This account includes all services necessary to operate the plant in order to demonstrate plant performance values and durations, including operations labor, consumables, spares, and supplies.
35	Design Services Off Site	This account covers engineering, design, and layout work conducted at the A/E home office and the equipment/reactor vendor's home office. Often preconstruction design is included here. These guidelines use the IAEA format for a standard plant (and equipment) design/construction/start-up only, and not the FOAK design and certification effort. (FOAK work is in the one-time deployment phase of the project and not included in the standard plant direct costs.) Design of the initial full-size (FOAK) reactor, which will encompass multiple designs at several levels (preconceptual, conceptual, preliminary, etc.), will be a category of its own under FOAK cost. This account also includes site-related engineering and engineering effort (project engineering) required during construction of particular systems, which recurs for all plants, and quality assurance costs related to design.
36	PM/CM Services Off Site	This account covers the costs for project management and management support for the activities listed in account 31, taking place at the reactor vendor, equipment supplier, and A/E home offices.

30: Indirect Services Cost (cont.)

37	Design Services On Site	This account includes the same items as in account 35, except that they are conducted at the plant site office or on-site temporary facilities instead of at an off-site office. This account also includes additional services such as purchasing and clerical services.
38	PM/CM Services On Site	This account covers the costs for project management and construction management support on the above activities taking place at the plant site. It includes staff for quality assurance, office administration, procurement, contract administration, human resources, labor relations, project control, and medical and safety-related activities. Costs for craft supervisory personnel are included account 32.

40: Owner's Costs

Code	Category	Description
41	Staff Recruitment and Training	This account includes costs to recruit and train plant operators before plant start-up or commissioning activities (account 33) or before demonstration tests (account 34).
42	Staff Housing	This account includes relocation costs, camps, or permanent housing provided to permanent plant operations and maintenance staff.
43	Staff Salary-Related Costs	This account includes taxes, insurance, fringes, benefits, and any other salary-related costs.
44	Other Owner's Costs	(No description details are given.)

50: Supplementary Costs

Code	Category	Description
51	Shipping and Transportation Costs	This account includes shipping and transportation costs for major equipment or bulk shipments with freight forwarding.
52	Spare Parts	This account includes spare parts furnished by system suppliers for the first year of commercial operation. It excludes spare parts required for plant commissioning, start-up, or the demonstration run.
53	Taxes	This account includes taxes associated with the permanent plant, such as property tax, to be capitalized with the plant.
54	Insurance	This account includes insurance costs associated with the permanent plant to be capitalized with the plant.
55	Initial Fuel Core Load	This account covers fuel purchased by the utility before commissioning, which is assumed to be part of the total capitalized investment cost. In the United States, the initial core is not usually included in the design/construction (overnight) cost sum to which interest during construction is added. Because the first core, however, will likely have to be financed along with the design/construction/start-up costs, its cost is included in overnight costs as part of capital at risk before revenues. This is a new account added to the modified IAEA account system.
58	Decommissioning Costs	This account includes the cost to decommission, decontaminate, and dismantle the plant at the end of commercial operation, if it is capitalized with the plant.

60: Financing During Construction

Code	Category	Description
61	Escalation	This account is typically excluded for a fixed-year, constant-dollar cost estimate, although it could be included in a business plan, a financing proposal, or regulatory-related documents.
62	Fees	This account includes any fees or royalties that are to be capitalized with the plant.
63	Interest During Construction	IDC is applied to the sum of all up-front costs (i.e., accounts 1 through 5 base costs), including respective contingencies. These costs are incurred before commercial operation and are assumed to be financed by a construction loan. The IDC represents the cost of the construction loan (e.g., its interest).
Sources		All capitalized financial costs are company-provided.
Default Value Calculation Methodology		Escalation and fees are zeroed out, as no uniform assumptions could be applied for these categories. Interest during construction is calculated as a combination of interested accrued during preconstruction and construction.

70: Operation and Maintenance

Code	Category	Description
71	O&M Staff	This account includes salary costs of O&M staff.
72	Management Staff	This account includes salary costs of operations management staff.
73	Salary-Related Costs	This account includes taxes, insurance, fringes, benefits, and any other annual salary-related costs.
74	Operating Chemicals and Lubricants	(No description details are given.)
75	Spare Parts	This account includes the cost of any operational spare parts, excluding capital plant upgrades or major equipment, that will be capitalized or amortized over some period of time or quantity of product.
76	Utilities, Supplies, and Consumables	This account includes the cost of water, gas, electricity, tools, machinery, maintenance equipment, office supplies, and similar items purchased annually.
77	Capital Plant Upgrades	This account includes upgrades to maintain or improve plant capacity, meet future regulatory requirements, or extend plant life.
78	Taxes and Insurance	This account includes property taxes and insurance costs, excluding those related to salary.
Sources		• ORNL 1987
Default Value Calculation Methodology		Default salary values and PWR headcounts are taken from the ORNL (1987) report (which, assumes a 1,100 MWe plant) and inflated by a factor of 2.1 to convert to 2016 dollars. For estimating on-site staff, we took the baseline headcount provided in the ORNL study and multiplied it by the ratio of the company's plant size to the generic source data plant size, raised to the power of 0.5. An exponent of less than 1 ensures that as plant size increases or decreases, the change in estimated staff is not linear. A subset of generic annual O&M costs, specifically categories 73, 76, and 78, was provided in the ORNL (1987) report and scales linearly with plant size. Categories where we did not have adequate reference information (categories 74, 75, and 77) were left for the companies to populate themselves.

80: Fuel Cost

Code	Category	Description
81	Refueling Operations	This account includes incremental costs associated with refueling operations.
84	Nuclear Fuel	This account includes annualized costs associated with the fuel cycle.
86	Fuel Reprocessing Charges	This account includes storage and reprocessing charges for spent fuel.
87	Special Nuclear Materials	This account includes costs associated with disposal or treatment (if necessary) of materials that are required on an annual basis, including heavy water, sodium, lead, helium, or other energy transfer mediums.
Sources	• Van Heek, Roelofs, and Ehlert 2012. • EIA 2017a.	
Default Value Calculation Methodology	We used fuel cost values from the sources listed above as a point of reference for the participating companies.	

90: Financing During Operation

Code	Category	Description
91	Escalation	This account is to be excluded from estimated costs for Generation IV nuclear energy systems, although it could be included in a business plan, a financing proposal, or regulatory-related documents.
92	Fees	This account includes the cost of annually incurred fees, such as for the reactor-licensing process, nuclear operating license, and similar.
93	Cost of Money	This account includes the value of money utilized for operating costs, which may be financed externally or through retained earnings.
Sources	All annualized financial costs are company-provided.	
Default Value Calculation Methodology	Accounts 91 and 93 are assumed to be $0 for generic reactor types, as the model uses fixed-year 2016 dollars (escalation is $0). Account 92 combines annual nuclear regulatory fees and reactor annual lease rate (if applicable). Fees (e.g., nuclear regulatory fees) are first scaled linearly based on the plant's capacity and then calculated on a per MWh basis by dividing by (Plant Capacity * Capacity Factor * 8,760 hours).	

APPENDIX D: EXTERNAL EXPERT REVIEW OF DRAFT REPORT

EIRP and EON are grateful to the companies that generously shared proprietary information about their work, and to the following people who reviewed a draft of this report and provided valuable comments. These individuals reviewed this work in their personal capacity, not as representatives of their respective organizations.

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