INL/RPT-23-72972
Revision 3

# Literature Review of Advanced Reactor Cost Estimates

Milestone M3CT-23IN1207065

October 2023

Abdalla Abou-Jaoude, Linyu Lin, Chandrakanth Bolisetti,
Elizabeth Worsham, Levi M Larsen, Aaron Epiney
*Nuclear Science & Technology Directorate, Idaho National Laboratory*

IES
Integrated Energy Systems

**INL/RPT-23-72972**
**Revision 3**

# Literature Review of Advanced Reactor Cost Estimates

## Integrated Energy Systems

**Abdalla Abou-Jaoude, Linyu Lin, Chandrakanth Bolisetti, Elizabeth Worsham, Levi M Larsen, Aaron Epiney**
**Nuclear Science & Technology Directorate, Idaho National Laboratory**

**October 2023**

**Idaho National Laboratory**
**Integrated Energy Systems**
**Idaho Falls, Idaho 83415**

**http://www.ies.inl.gov**

**Prepared for the**
**U.S. Department of Energy**
**Office of Nuclear Energy**
**Under DOE Idaho Operations Office**
**Contract DE-AC07-05ID14517**

*Page intentionally left blank*

# EXECUTIVE SUMMARY

A comprehensive review of existing literature on advanced reactor cost estimations was conducted in the form of a meta-study with over 30 references evaluated. Datapoints were aggregated, escalated to 2019 values, then analyzed with equal weighting to identify projected nuclear cost ranges that can be further refined in future work. A summary of these results is provided in Table 1. The ranges consist of low/medium/high estimates (based on quartiles) for capital and operating costs that can be adjusted with care using various correction factors (based on learning, numbers of plants per site, etc.). Reference breakdowns (in costs, based on a code of account structure) are provided for the main four types of advanced reactors. It is important to emphasize that the goal of the study is not to infer exact cost projections for nuclear energy, but rather to provide useful ranges of where costs may lie. These can be leveraged as inputs to models optimizing energy portfolios.

Table 1. Summary table with identified values for advanced nuclear cost estimates (excludes microreactors). The values are for a build between a first and Nth of a kind (BOAK). All estimates are in 2019 USD.

| **Variable** | | **Low** | **Medium** | **High** | |
|---|---|---|---|---|---|
| **BOAK Overnight Capital Cost (OCC)** | | $4,000 /kWe | $6,000 /kWe | $7,000 /kWe | |
| **Operating Expenses (OPEX)** | | $15 /MWh | $25 /MWh | $35 /MWh | |
| | | | | | |
| **First-of-a-kind Premium Multiplier** | | 1.3 | 1.6 | 2.1 | |
| **Learning Rate** | | 5% | 10% | 15% | |
| **Multi-unit OCC Exponent** | | 0.8 | 0.825 | 0.850 | |
| **Multi-Unit OPEX Multiplier** | | 0.5 | 0.624 | 0.7 | |
| | | | | | |
| | | **PWR** | **SFR** | **HTGR** | **MSR** |
| **Overnight Costs** | | | | | |
| **10** | **Preconstruction Costs** | 2.35% | 5.30% | 1.19% | 2.74% |
| **20** | **Direct Costs** | 39.65% | 49.55% | 40.25% | 39.41% |
| **21** | **Structures** | 10.33% | 11.03% | 5.66% | 9.59% |
| **22** | **Reactor Equipment** | 12.50% | 23.95% | 14.79% | 14.51% |
| **23** | **Energy Conversion System** | 8.76% | 3.88% | 9.13% | 8.16% |
| **24** | **Electrical Equipment** | 3.92% | 5.56% | 8.11% | 4.55% |
| **25** | **Heat Rejection System** | 1.85% | 3.31% | 2.56% | 1.16% |
| **26** | **Miscellaneous Equipment** | 2.29% | 1.81% | 0.00% | 1.46% |
| **30** | **Indirect Costs** | 44.16% | 34.33% | 44.83% | 43.90% |
| **40** | **Owner Costs** | 12.57% | 9.77% | 12.76% | 12.50% |
| **50** | **Supplementary Costs** | 1.28% | 1.05% | 0.96% | 1.45% |
| **Annualized Costs** | | | | | |
| **70** | **Operating Staff Costs** | 95.98% | 58.14% | 55.62% | 98.18% |
| **80** | **Annualized Fuel Costs** | 4.02% | 41.86% | 44.38% | 1.82% |

# ACKNOWLEDGEMENTS

This manuscript was authored at Idaho National Laboratory by Battelle Energy Alliance LLC under contract no. DE-AC07-05ID14517 with the U.S. Department of Energy (DOE). This work was prepared for the U.S. DOE Office of Nuclear Energy (DOE-NE) via funding by the Integrated Energy Systems (IES) campaign.

The authors would like to acknowledge Andrew Foss and Brent Dixon for their support with reviewing and improving the document. They provided invaluable insights into the evaluation. The authors also thank Kelsey Gaston for her diligent editorial review of the document.

*Page intentionally left blank*

# CONTENTS

# FIGURES

# TABLES

*Page intentionally left blank*

# ACRONYMS

| | |
|---|---|
| AHTR | Advanced High-Temperature Reactor |
| ATB | Annual Technology Baseline |
| APEA | Aspen Process Economic Analyzer |
| BOAK | Between of a first and Nth kind |
| BOP | Balance of plant |
| CANES | Center for Advanced Nuclear Energy Systems |
| COA | Code of Account |
| DOE | Department of Energy |
| DMSR | Denatured Molten Salt Reactor |
| D&D | Deactivation & Decommissioning |
| EEDB | Energy economic data base |
| EMWG | Economic Modeling Working Group |
| FOAK | First-of-a-kind |
| GDP | Gross Domestic Product |
| GHG | Greenhouse Gas |
| IES | Integrated Energy Systems |
| INL | Idaho National Laboratory |
| LSPBR | Large-Scale Prototype Breeder Reactor |
| LWR | Light Water Reactor |
| MHTGR | Modular High-Temperature Gas-Cooled Reactor |
| MSR | Molten Salt Reactors |
| MUE | Multi-unit exponent |
| NEI | Nuclear Energy Institute |
| NGNP | Next Generation Nuclear Plant |
| NOAK | Nth-of-a-kind |
| NSRST | Non-safety-related with special treatment |
| NSSS | Nuclear Steam Supply System |
| OCC | Overnight Capital Cost |
| O&M | Operation & Maintenance |
| PRISM | Power Reactor Innovative Small Module |
| RAVEN | Risk Analysis and Virtual ENvironments |
| ROM | Rough order of magnitude |

| | |
|---|---|
| SA&I | Systems Analysis & Integration |
| SFR | Sodium Fast Reactors |
| SR | Safety-related |
| UQ | Uncertainty quantification |

*Page intentionally left blank*

# Literature Review of Advanced Reactor Cost Estimates

## 1. BACKGROUND

Nuclear energy can provide consistent, dispatchable power to meet electricity demands while also supplying high-quality heat that can meet energy needs beyond the electricity sector—all without emission of $CO_2$ or other greenhouse gases (GHGs). To fully assess these benefits, it is necessary to better characterize the potential role or roles for nuclear energy amid the growing field of variable renewable generation technologies.

Integrated Energy Systems (IES) are cooperatively controlled systems that dynamically apportion thermal and/or electrical energy to provide responsive generation to the power grid. They comprise multiple subsystems, which may or may not be geographically co-located, including a nuclear heat generation source, a turbine that converts thermal energy to electricity, at least one renewable energy source, and one or more industrial processes that utilize heat and/or power from the energy sources to produce a commodity-scale product. IES design and optimization would consider both technical performance and economic viability within various deployment markets.

Coupled energy generation systems (e.g., novel reactor technologies) and advanced industrial applications may not be commercially deployed at present, but the necessary steps toward technology maturation are being addressed through various federal R&D and private industry investments. The role of modeling and simulation within IES is to support the demonstration of new coupled integrated technologies along every step of technology maturation from the strategic analysis of preferred system architecture to preliminary design, to laboratory testing, up to full commercial testing and integration. To achieve this role, modeling and simulation must be able to assess the technical performance and the economic viability of potential IES. To do so, accurate inputs, e.g., overnight capital cost data (with well understood uncertainty), are crucial.

To date, IES studies have used cost functions for the various component and system sizes that are generated from a number of sources, including actual quotations from vendors, historical data in literature, and latest publicly available data obtained from the Aspen Process Economic Analyzer (APEA-V11) [1]. Cost data (or more specifically "cost functions") development has included the creation of cost trends derived from APEA-V11 data as a function of varying system size. While these information sources are adequate for non-nuclear components, e.g., (chemical) industrial plants and heat extracting technologies (heat exchangers, valves, etc.), they include significant uncertainty for (advanced) nuclear. Accurate capital and operational cost data for advanced nuclear concepts is critical for meaningful technoeconomic analyses. Providing a basis for nuclear cost estimates can enable broad evaluation of deployment potential of the technology, as well as cost evaluation of potential non-electric products from nuclear plants. This is expected to be useful even beyond the scope of the IES program. Capacity expansion models would all benefit from more robust cost estimates for nuclear reactors. Similarly, utilities and industries considering options for de-carbonization of their operations, could also benefit from additional insights on potential cost projections for nuclear technology.

To this end, this work focuses on solidifying resources for retrieving accurate costing data for the advanced reactor concepts that can be used in IES models and use cases. The starting point is a detailed review of existing literature on advanced reactor cost evaluation, distilling important information for energy system evaluations. Future efforts to add to the existing literature would build on this report focusing on gaps and areas for potential improvement.

# 2. SOURCES AND METHODOLOGY FOR COST ESTIMATION

This report provides a detailed overview of the existing open literature on advanced reactor costs. The results of this overview are encapsulated in a three-tier analysis that can be referenced for more accurate advanced reactor cost estimations in future research. Each of the three tiers has a corresponding level of fidelity:

- Tier 1 only considered estimates in the literature on levelized cost of electricity (LCOEs). This level of analysis is limited however, as it does not necessarily provide a useful basis of comparison against variable energy sources (or any other energy source with low capacity factors) [2]. Furthermore, LCOEs have limited value beyond electricity generation.
- Tier 2 provides additional granularity and describes nuclear costs in terms of capital and operating costs. This more granular breakdown is much better suited for grid-modeling (e.g., capacity expansion models) and utility-scale planning.
- Tier 3 provides the most granular breakdown of advanced reactor costs using the Code of Account framework. This provides a higher-level of fidelity that can be needed for certain analyses. For instance, if existing infrastructure can be leveraged and not all costs need to be accounted in the cost (e.g., in the case of leverage the switchyard for a ‘coal-to-nuclear’ transition for instance [3]). Another scenario where this level of detail is needed is in the case of a heat-only use case where the cost of the turbine and associated systems does not need to be included.

## 2.1 Overview of Methodology and Limitations

Historically, the task of producing accurate nuclear cost estimate recommendations and techniques has been fraught with complications. The lack of public data on advanced reactor constructions (limited deployment in the U.S. as of the time of writing) drives the reliance on estimates and projections rather than physical observations. However, leveraging estimates introduces an entire gamut of associated issues:

1. Inconsistencies between estimates and their corresponding methodology.
2. Potential biases in estimates (for instance due to stance on nuclear energy as a whole).
3. Incomplete data in estimates (detailed breakdowns may be hidden in some cases).
4. Data specificity and applicability across various use case (e.g., electric versus non-electric).
5. Lack of range in cost estimate from references (most provide single datapoint).
6. Sparsity of information on underlying assumptions for estimate (e.g., if first or Nth of a kind).
7. Gaps in time between the estimates (requiring escalation to adjust the baselines).
8. Variations in the level of maturity of the estimate (very detailed versus high-level)
9. Variations in the level of maturity of the design on which estimates are based (some estimates are based on very mature concepts while others on early designs)

While leveraging estimates from literature has intrinsic constraints, additional challenges arise from processing of this data. The methodology followed in this study has several limitations; key ones are summarized below:

1. The study assigns equal weights to all estimates in the literature. This is inherently limiting since cost datasets relying on observed costs are weighed equally to those that are entirely on projected estimates. Similarly older datasets are weighed equally to more recent ones. However, typically the more reliable estimates leveraging observed costs are often the oldest used here. This creates a significant challenge in determining how to best adjust weights for a given estimate. As a result, this report elected not to opine on how estimates should be weighted and instead treats each estimate the same, with equal weighting.
2. Inferring insights from the dataset compiled (even with equal weighting) is fraught with challenges as well. Deductions from data aggregation techniques may be inherently swayed based on the number, biases, and inconsistencies in datapoints. Here, the recommended cost ranges were obtained by splitting cost data into quartiles. From a statistical standpoint the use of quartiles is less susceptible to the bias produced from major outliers than relying on averages or min/max values.
3. The data collected in this report contains several inconsistencies in what they do and do not include as part of their estimates. Some estimates include financing costs, while others do not. The same can be said for owners costs, pre-construction costs, and supplementary costs. This is yet another complication of comparing nuclear costs. This study opted to compare all values equally and use them to infer total overnight capital costs for a nuclear plant. While the approach is imperfect, the end results were still found to agree well with other similar meta-studies conducted in the literature.

Despite of these challenges and the complexity of the task, there still exists a strong need for more comprehensive evaluations of advanced nuclear power plants cost estimations. However, this study does not pretend to be the ultimate reference for nuclear reactor costs. Instead, it provides a useful survey of the existing literature of nuclear cost estimates and attempts to distill useful insights and trends from the data. This is expected to provide additional, albeit limited, confidence in the range of potential costs to be expected for future deployments of this technology, anchored in the existing literature on the topic. The aggregation of multiple references into a single document is expected to be useful as well. While several studies aggregate cost data for nuclear reactors, no other study was found to be as comprehensive as the one presented here (especially for nuclear overnight costs). As a result, this report is expected to set a foundation for future work. Aggregating data this extensively can help facilitates future efforts that can build on this study and refine identified values by post-processing estimates or adding to them.

In light of the broad ranging challenges discussed above, the meta-study presented here, will intentionally ignore several potential discrepancies in cost estimation between the various sources considered. Accounting for all these nuances will be left to future efforts. However, the study still tackles several of these disparities by:

- Capturing key metrics (LCOE, Overnight, etc.) to compare across estimates.
- Capturing important parameters that may or may not impact cost estimates (e.g., reactor type, size, maturity)
- Quantifying the observable ranges in estimates.
- Focusing primarily on reviewed, and well-respected academic sources (which are clearly and transparently listed).
- Reducing the impact of significant outliers in the data (e.g., by the use of quartiles rather than minima for ‘low’ range estimates).
- Escalating all cost estimates to the reference year of 2019 USD.

To achieve this, the study provides a comprehensive list of all references considered and tabulating key metrics that were leveraged in the analysis. Then, these values are escalated to a common year in order to provide a basis for comparison. This dataset was queried in an attempt to elucidate some (not all) important drivers of costs for nuclear reactors. This includes potential factors such as reactor technology type, reactor size/power output, maturity of the technology, assumed learning from deployment, as well as pooling of infrastructure and resources between plants. This list of factors/biases is not exhaustive. However, it still provides a useful starting point to yield more accurate insights on advanced reactor costs and their potential drivers.

## 2.2 Overview of Considered Literature

Note that cost estimates from the Advanced Reactor Demonstration Program (ARDP) were not included because public statements regarding overall costs do not include breakdowns of reactor costs against other expenses. Reference [4] highlights how one of the ARDP awardees intends to use the total budget for completing the design, obtaining license approval, and construction of a fuel fabrication facility, in addition to the reactor demonstration costs.

Table 2 provides an overview of the various references considered in this study. The list is not intended to be comprehensive but was rather geared towards capturing a broad range of considerations (in terms of reactor type, size, etc.). The key values extracted from each reference were tabulated without any additional manipulation at this stage.

The review encompasses a wide range of advanced reactors of various sizes: large, small modular (SMR), and microreactors. It also considered a wide range of technology types, including Pressurized Water Reactors (PWRs), Sodium Fast Reactors (SFRs), High-Temperature Gas-cooled Reactors (HTGRs), and Molten Salt Reactors (MSRs). Reactor estimates are also categorized in terms of First-of-a-Kind (FOAK) and Nth-of-a-Kind (NOAK). The review collected information relating to estimated overnight costs, Operation & Maintenance (O&M or OPEX), and levelized costs of electricity (LCOE). Information on the power-level of the plant and the number of units per plant is also provided. The table intends to transparently lay-out the various data points extracted from the literature. It should be mentioned – as previously disclosed – that the dataset contains several inconsistencies in cost contributors that are or are not included in several instances. Some of these inconsistencies are highlighted in Appendix A. Despite these limitations, it was still possible to infer useful insights from the aggregated data. Note that cost estimates from the Advanced Reactor Demonstration Program (ARDP) were not included because public statements regarding overall costs do not include breakdowns of reactor costs against other expenses. Reference [4] highlights how one of the ARDP awardees intends to use the total budget for completing the design, obtaining license approval, and construction of a fuel fabrication facility, in addition to the reactor demonstration costs.

Table 2. Summary of total costs for four categories of reactor concept based on estimates from 30 references. Note that all costs provided here are based on the reference year (shown in the dollar sign subscript). Escalated costs are provided in Appendix A.

| | **Ref.** | **Reactor Concept** | **Learning** | **Units** | **Power** | **Specific costs** | **LCOE** | **OPEX** |
|---|---|---|---|---|---|---|---|---|
| **PWR** | [5] | NuScale iPWR | FOAK | 12 | 1920MWth/570MWe | 5,100$\$_{2015}$/kWe | 114$\$_{2015}$/MW-hr | — |
| | [6] | NuScale iPWR | NOAK | 12 | 685MWe | 3,856$\$_{2018}$/kWe | — | — |
| | [7] | NuScale VOYGR | NOAK | 12 | 924MWe | 2,850$\$_{2018}$/kWe | — | — |
| | [8] | NuScale/UAMPS | FOAK | 6 | 462MWe | 20,139$\$_{2022}$/kWe | 119$\$_{2022}$/MW-hr | |
| | [9] | SMART iPWR | — | — | — | 5,600$\$_{2014}$/kWe | 105$\$_{2014}$/MW-hr | 25$\$_{2014}$/MW-hr |

|  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|
|  | [10] | NuScale SMR | — | — | 1920-2400MWth/600-720MWe | — | 51-54$\$_{2019}$/MW-hr<br>112$\$_{2016}$/MW-hr [11]<br>101$\$_{2016}$/MW-hr [12] | — |
|  | [13] | NuScale | — | — | 600MWe | — | 65$\$_{2015}$/MW-hr | — |
|  | [14] | SMR | — | — | 570MWe | — | 80$\$_{2017}$/MW-hr | — |
|  | [15] | SMR | — | 12 | 600MWe | 6,191$\$_{2019}$/KWe | — | — |
|  | [16] | SMR | FOAK | 4 | 600MWe | 3,800$\$_{2020}$/MW-hr | 95$\$_{2020}$/MW-hr | 22$\$_{2020}$/MW-hr |
|  | [16] | SMR | NOAK | 4 | 600MWe | 2,000$\$_{2020}$/MW-hr | 44$\$_{2020}$/MW-hr | 15$\$_{2020}$/MW-hr |
|  | [10] | GEH BWRX-300 | — | — | 870MWth/300MWe | — | 44–51$\$_{2019}$/MW-hr | — |
|  | [17] | PWR-12 | FOAK | 1 | 3417MWth/1144MWe | 6,345$\$_{2017}$/kWe | — | — |
|  | [17] | PWR-12 | NOAK | 1 | 3417MWth/1144MWe | 3,650$\$_{2017}$/kWe | — | — |
|  | [17] | AP1000 | FOAK | 1 | 3417MWth/1144MWe | 6,671$\$_{2017}$/kWe | — | — |
|  | [17] | AP1000 | NOAK | 1 | 3415MWth/1100MWe | 3,838$\$_{2017}$/kWe | — | — |
|  | [18] | AP1000 | FOAK | 1 | 3415MWth/1100MWe | 7,349$\$_{2022}$/kWe | 81$\$_{2022}$/MW-hr | — |
|  | [2] | PWR | FOAK | 1 | 3415MWth/1100MWe | 6,154$\$_{2018}$/kWe | — | — |
|  | [2] | PWR | NOAK | 1 | 3415MWth/1100MWe | 6,986$\$_{2014}$/kWe | — | — |
|  | [15] | PWR | — | 2 | 2156 MWe | 6,041$\$_{2019}$/KWe | — | — |
|  | [10] | PWR | — | 2 | 2256MWe | 6,317$\$_{2019}$/KWe | 82$\$_{2019}$/ MW-hr | 25$\$_{2019}$/ MW-hr |
|  | [19] | PWR | — | — | — | — | 141-221$\$_{2023}$/MW-hr | 19-21$\$_{2023}$/MW-hr |
|  | [20] | PWR12BE | NOAK | 1 | 3417MWth/1144MWe | 3,054$\$_{2011}$/kWe | — | — |
|  | [20] | PWR12ME | FOAK | 1 | 3417MWth/1144Mwe | 5,305$\$_{2011}$/kWe | — | — |
|  | [20] | PWR Improved | — | 1 | 3417MWth/1144Mwe | 2,534$\$_{2011}$/kWe | — | — |
| **HTGR** | [17] | NGNP | — | 1 | 275MW | 9,900$\$_{2017}$/kWe | — | — |
|  | [9] | HTGR | — | — | — | 6,600$\$_{2015}$/kWe | 128$\$_{2015}$/MW-hr | 30$\$_{2015}$/MW-hr |
|  | [17] | MIGHTR | — | 1 | 350MWth/154MWe | 7,346$\$_{2017}$/kWe | — | — |
|  | [21] | NGNP | FOAK | 1 | 350MWth/156MWe | 20,994$\$_{2009}$/kWe | — | — |
|  | [21] | NGNP | FOAK | 1 | 600MWth/267MWe | 14,479$\$_{2009}$/kWe | — | — |
|  | [21] | NGNP | NOAK | 1 | 350MWth/154MWe | 7,324$\$_{2009}$/kWe | — | — |
|  | [21] | NGNP | NOAK | 1 | 600MWth/267MWe | 5,841$\$_{2009}$/kWe | — | — |
|  | [2] | NGNP | — | 4 | 2400MWth/1000MWe | 5,246$\$_{2009}$/kWe | 114$\$_{2009}$/MW-hr | — |
|  | [17] | NGNP | — | 4 | 1100 MW | 4,814$\$_{2017}$/kWe | — | — |
|  | [21] | NGNP | NOAK | 4 | 1400MWth/624MWe | 5,720$\$_{2009}$/kWe | — | — |
|  | [17] | MIGHTR | NOAK | 4 | 1400MWth/616MWe | 3,585$\$_{2017}$/kWe | — | — |
|  | [21] | NGNP | NOAK | 4 | 2400MWth/1068MWe | 4,663$\$_{2009}$/kWe | — | — |
|  | [22] | NGNP | — | 4 | 2400MWth/1068MWe | 5,600$\$_{2018}$/kWe | — | — |
|  | [22] | HC-HTGR | FOAK | 4 | 920MWe | 4,550$\$_{2018}$/kWe | — | — |
|  | [22] | HC-HTGR | 10-OAK | 4 | 920MWe | 3,000$\$_{2018}$/kWe | — | — |
|  | [23] | MHTGR-SC | FOAK | 4 | 1800MWth/693MWe | 3,153$\$_{1992}$/kWe | — | — |
|  | [23] | MHTGR-SC | NOAK | 4 | 1800MWth/693MWe | 2,347$\$_{1992}$/kWe | 50$\$_{1992}$/MW-hr | 8$\$_{1992}$/MW-hr |
|  | [23] | MHTGR-GT/IC | FOAK | 4 | 1800MWth/806MWe | 3,290$\$_{1992}$/kWe | — | — |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | [23] | MHTGR-GT/IC | NOAK | 4 | 1800MWth/806MWe | $2,458\$_{1992}$/kWe | $48\$_{1992}$/MW-hr | $6\$_{1992}$/MW-hr |
| | [23] | MHTGR-GT/DC | FOAK | 4 | 1800MWth/869MWe | $2,656\$_{1992}$/kWe | — | — |
| | [23] | MHTGR-GT/DC | NOAK | 4 | 1800MWth/869MWe | $1,908\$_{1992}$/kWe | $39\$_{1992}$/MW-hr | $5\$_{1992}$/MW-hr |
| | [24] | HTGR | NOAK | — | 1124MWe | $5,469\$_{2017}$/kWe | $55\$_{2017}$/MW-hr | — |
| **SFR** | [2] | SFR | — | 4 | 3360MWth/1100MWe | $5,632\$_{2013}$/kWe | $113\$_{2013}$/MW-hr | — |
| | [25] | 4S Sodium | — | 1 | 30MWth | — | $130\text{-}290\$_{2009}$/MW-hr | — |
| | [26] | LSPB | — | 1 | 1100MWe | $4,734\$_{2013}$/kWe | — | — |
| | [27] | ABR1000 | — | 1 | 380MWe | $5,612\$_{2017}$/kWe | — | — |
| | [28] | S-PRISM | — | 4 | 1520MWe | $2,664\$_{2005}$/kWe | $39\$_{2005}$/MW-hr | — |
| | [28] | S-PRISM | — | 4 | 1520MWe | $3,046\$_{2005}$/kWe | $60\$_{2005}$/MW-hr | — |
| | [29] | S-PRISM | — | 2 | 1651MWe | $1,334\$_{1996}$/kW | $32\$_{1996}$/MW-hr | — |
| | [28] | S-PRISM Mod B | — | 6 | 1866MWe | $2,073\$_{2005}$/kWe | $39\$_{2005}$/MW-hr | — |
| | [28] | S-PRISM Mod B | — | 6 | 1866MWe | $2,371\$_{2005}$/kWe | $55\$_{2005}$/MW-hr | — |
| | [30] | S-PRISM Mod B | — | 6 | 1866MWe | $1,554\$_{2004}$/kWe | $40\$_{2004}$/MW-hr | — |
| | [24] | LSPB | NOAK | — | 1311Mwe | $4,240\$_{2017}$/kWe | $80\$_{2017}$/MW-hr | — |
| **MSR** | [2] | AHTR | — | 1 | 3000MWth/1350MWe | $5,217\$_{2011}$/kWe | $111\$_{2011}$/MW-hr | — |
| | [2] | MSR | — | 1 | 2275MWth/1000MWe | $6,113\$_{2011}$/kWe | $119\$_{2011}$/MW-hr | — |
| | [2] | FHR | — | 12 | 2904MWth/1330MWe | $5,423\$_{2015}$/kWe | $135\$_{2015}$/MW-hr | — |
| | [31] | DMSR | — | 1 | 1000MW | $6,53\$_{1978}$/kWe | — | — |
| | [20] | AHTR | NOAK | 1 | 3400MWth/1530MWe | $3,384\$_{2011}$/kWe | — | $34\text{-}60\$_{2011}$/MW-hr |
| | [24] | MSR | NOAK | — | 190-1000MWe | $3,664\$_{2017}$/kWe | $51\$_{2017}$/MW-hr | $19\$_{2017}$/MW-hr |
| **Microreactor** | [32] | Reference microreactor | FOAK | 1 | 10MWth/5MWe | $10,000\$_{2019}$/kWe | $150\$_{2019}$/MW-hr | $69\$_{2019}$/MW-hr |
| | [32] | Reference microreactor | FOAK | 1 | 10MWth/5MWe | $15,000\$_{2019}$/kWe | $310\$_{2019}$/MW-hr | $103\$_{2019}$/MW-hr |
| | [32] | Reference microreactor | FOAK | 1 | 10MWth/5MWe | $20,000\$_{2019}$/kWe | $410\$_{2019}$/MW-hr | $137\$_{2019}$/MW-hr |
| | [32] | Reference microreactor | NOAK | 1 | 10MWth/5MWe | $3,996\$_{2019}$/kWe | $80\$_{2019}$/MW-hr | — |
| | [32] | Reference microreactor | NOAK | 1 | 10MWth/5MWe | $8,276\$_{2019}$/kWe | $200\$_{2019}$/MW-hr | — |
| | [32] | Reference microreactor | NOAK | 1 | 10MWth/5MWe | $14,973\$_{2019}$/kWe | $340\$_{2019}$/MW-hr | — |
| | [33] | Design A | FOAK | 1 | 5MWth/1.8MWe | $65,445\$_{2017}$/kWe | $2174\$_{2017}$/MW-hr | $112\$_{2017}$/MW-hr |
| | [33] | Design A’ | FOAK | 1 | 8MWth/2.9MWe | $19,241\$_{2017}$/kWe | $363\$_{2017}$/MW-hr | $122\$_{2017}$/MW-hr |
| | [33] | Design A’ | NOAK | 1 | 8MWth/2.9MWe | $6,575\$_{2017}$/kWe | $135\$_{2017}$/MW-hr | $53\$_{2017}$/MW-hr |

As shown in the summary table, specific overnight costs vary greatly between different sources and reactor types. Potential trends will be investigated in further detail in Section 2.4. At this stage, it is already apparent that the main drivers for some reactors can be attributed to the level of learning (FOAK and NOAK). For instance, PWRs with best and improved experiences are half the price for a FOAK reactor. Interestingly, costs of several smaller reactors are comparable to those of larger reactors (e.g., NuScale FOAK). On the other hand, the cost estimates for HTGRs in particular, differ substantially. This can be attributed to FOAK overrun assumptions and lower technology maturity level relative to PWRs. In general, reactors with higher thermal/electrical power generations usually have lower estimates of total costs. However, this topic has been consistently debated in the literature. With some arguing that large reactors appear to experience diseconomies of scale due to the challenge of executing such complex projects [24] [34] [35], while others point that size in and of itself was not the leading cost of these escalations [36].

## 2.3 Cost Escalation Methodology

In order to cross-compare costs from various years, all estimates were escalated to the base year of 2019. This year was used as a reference to avoid the recent inflationary trends in the global economy as well as the adverse impact of a global pandemic. While the reference is several years from the time of publishing of the report, it still provides a useful basis for comparison. It is also important that some estimates in the literature are themselves based on older datasets that may have been escalated using different methodologies than the one leveraged here.

For the purposes of this study, the methodology recommended by the Advanced Fuel Cycle Cost Basis Report (CBR) [37] was initially leveraged. The report provides a cost factor for nuclear reactor cost estimation for every year between 1978 until 2017 (time of publication of this report). These are nuclear-specific escalation factors and are therefore deemed to be suitable for the purposes of this analysis. For cost estimates beyond 2017, standard production indices from the U.S. Bureau of Labor Statistic were used. Specifically, the “New Industrial Building Construction Cost Factor” [38] was selected as a suitable proxy for nuclear new build. In light of the lack of new nuclear constructions in the recent decade to baseline escalation factors, the industrial building construction trend was assumed to be applicable for the five remaining years considered in this study. Table 3 highlights the two different cost factors used for cost escalation and how they were combined and re-baselined to 2019. It is important to note that there are a range of other approaches for accounting for escalating costs. The approach used here was primarily selected for its simplicity.

Table 3. Cost factors leveraged for cost escalation to 2019 USD. The factors combine CBR data up to 2017 and the factorized indexes for new industrial building construction passed that year.

| | Cost Basis Report Cost Factor 2017 Base | New Industrial Building Construction Cost Factor 2017 Base | New, Combined Cost Factor 2019 Base |
|---|---|---|---|
| **1978** | 5.95 | | 6.60 |
| **1979** | 5.61 | | 6.22 |
| **1980** | 5.32 | | 5.90 |
| **1981** | 4.82 | | 5.35 |
| **1982** | 4.41 | | 4.89 |
| **1983** | 4.06 | | 4.50 |
| **1984** | 3.76 | | 4.17 |
| **1985** | 3.51 | | 3.89 |
| **1986** | 3.4 | | 3.77 |
| **1987** | 3.3 | | 3.66 |
| **1988** | 3.2 | | 3.55 |
| **1989** | 3.11 | | 3.45 |
| **1990** | 3.02 | | 3.35 |
| **1991** | 2.92 | | 3.24 |
| **1992** | 2.83 | | 3.14 |
| **1993** | 2.74 | | 3.04 |
| **1994** | 2.65 | | 2.94 |
| **1995** | 2.57 | | 2.85 |
| **1996** | 2.55 | | 2.83 |
| **1997** | 2.5 | | 2.77 |
| **1998** | 2.49 | | 2.76 |
| **1999** | 2.46 | | 2.73 |
| **2000** | 2.44 | | 2.71 |
| **2001** | 2.37 | | 2.63 |
| **2002** | 2.26 | | 2.51 |
| **2003** | 2.14 | | 2.37 |
| **2004** | 1.97 | | 2.19 |
| **2005** | 1.79 | | 1.99 |
| **2006** | 1.34 | | 1.48 |
| **2007** | 1.05 | | 1.16 |
| **2008** | 1.09 | 1.16 | 1.21 |
| **2009** | 1.14 | 1.13 | 1.26 |
| **2010** | 1.13 | 1.16 | 1.25 |
| **2011** | 1.11 | 1.14 | 1.23 |
| **2012** | 1.06 | 1.11 | 1.18 |
| **2013** | 1.07 | 1.09 | 1.19 |
| **2014** | 1.05 | 1.05 | 1.16 |
| **2015** | 1.03 | 1.03 | 1.14 |
| **2016** | 1.02 | 1.03 | 1.13 |
| **2017** | 1.00 | 1.00 | 1.11 |
| **2018** | | 0.95 | 1.06 |
| **2019** | | 0.90 | 1.00 |
| **2020** | | 0.88 | 0.97 |
| **2021** | | 0.83 | 0.92 |
| **2022** | | 0.68 | 0.75 |

Costs were then escalated based on Equation 1 below for each reference in Table 2. The new adjusted values are shown in Appendix A.

$$Costs_{2019} = Cost_i \times Factor_i \qquad (1)$$

Baselining the costs for the same year enables further analysis of the dataset by removing noise in the data created by inflation. As an example, if a reactor cost was estimated to be \$2,458/kWe in 1992 (which may seem like a competitive cost), applying the escalation factor would result in a new value of \$7,712/kWe in 2019 USD (which is on the higher end of the spectrum of expected costs). This highlights the impact of cost escalation and how it can distort conclusions in cost estimation. Because escalation is a relatively imperfect science, it is a notable source of potential error in the analysis shown here. However, as previously argued, it is still and important exercise to attempt to baseline a disparate source of various estimates in advanced reactor costs.

The resulting re-normalized dataset is then plotted in Figure 1. All points were escalated to 2019 USD. The spread in the data is not as large as one would expect based on the interpretation of the raw data alone. The majority of data points do appear to be clustered between \$2,000/kWe and \$8,000/kWe.

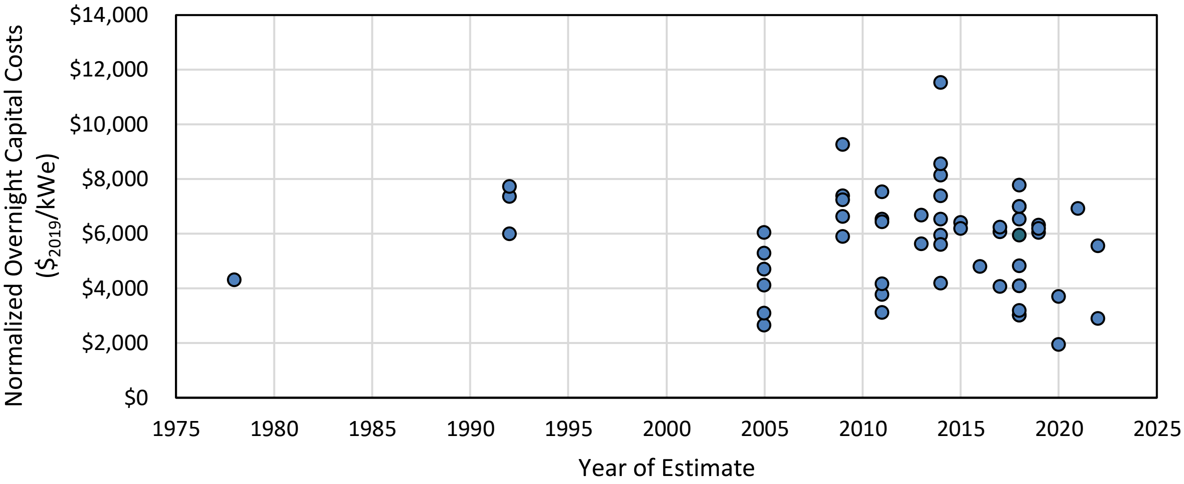


Figure 1. Overview of the overnight capital cost estimate range re-baselined to 2019 USD.

## 2.4 Evaluating Potential Data Groupings

When discussing nuclear costs, terms such as capital cost and overnight capital cost (OCC) are often used interchangeably without considering the differences between the two. Capital cost is a reference to fixed, one-time expenses, that are incurred when building facilities, purchasing equipment, and buying other depreciable goods. These expenses are typically in the form of construction material costs, component costs, labor costs, installation costs, etc. Overnight capital cost refers to the cost of the very same goods, but it implies that the cost is incurred as if the project was completed overnight. This means OCC ignores financing costs during construction. Subsequently, when this report refers to overnight capital cost it should be noted that interest incurred during construction is not accounted for (Note again the discussion from section 2.1 on this issue and the potential for some upward bias in this area). These costs were primarily leveraged to elucidate trends in the data. Cost estimates of the four reactor types (PWR, HTGR, SFR, MSR) were found to be statistically comparable as described in more detail in the following section.

### Grouping Based on Reactor Type

The study first set out to identify trends in OCC based on the type of reactor. Figure 2 plots the specific costs of different reactor types against the reactor power. A general trend towards lower costs with increasing plant power outputs can be seen. Another observable trend is the significant overlap between the various reactor types. At first look, there do not appear to be substantial variations in costs based on the type of technology. This is in-line with observations made in [2] which also concluded that it remains unclear if the reactor technology type would impact costs in and of itself.

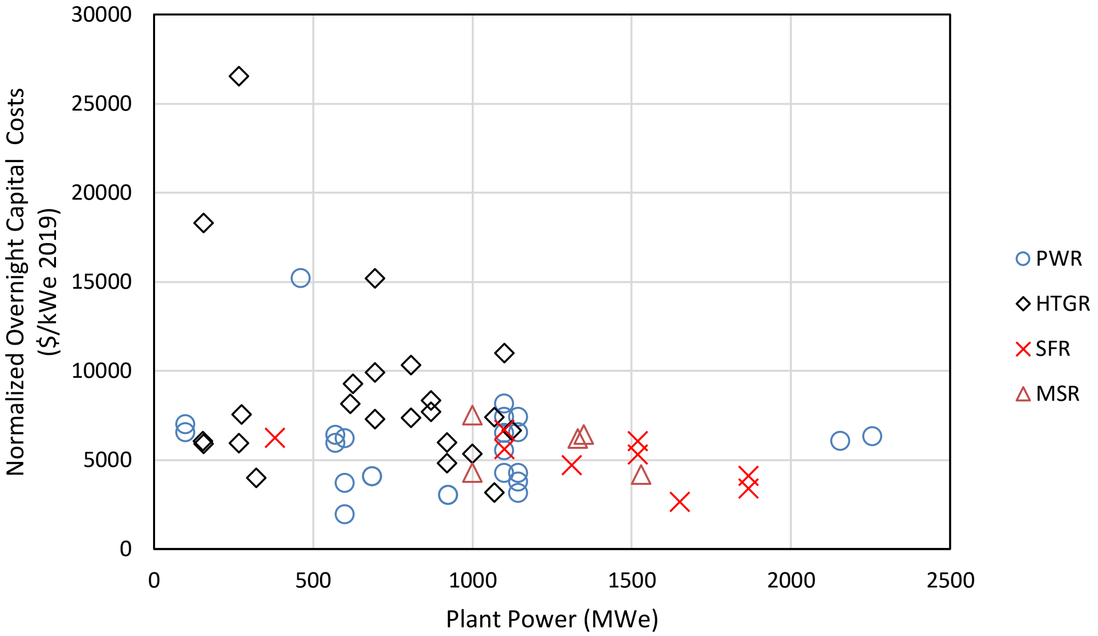


Figure 2: Scatter plot of overnight capital costs versus plant power rates for four major types of advanced reactors. Note that microreactors cost estimates are excluded from this initial plot for visualization clarity.

Upon further inspection, this is confirmed in the whisker plot in Figure 3. A significant overlap is observed between the various reactor types. The highest PWR cost (15,196$$_{2019}$/kWe) is from reference [8] for NuScale/UAMPS. The highest HTGR costs (18,313$$_{2019}$/kWe and 26,553$$_{2019}$/kWe) are from reference [21] for single-unit FOAK NGNP with 600 MWth and 350 MWth, respectively. There appear to be slightly more variations in the minima across reactor types. This could be attributed to potential biases of estimates. For instance, a vendor may be encouraged to project the lowest possible estimate for their reactor cost to position it as attractive for investments. Another reason for the deviations in minima is due to lack of maturity in the design at the time of an estimate. Reference [2] specifically identifies a track record in the nuclear industry to consistently underestimate costs early in a project, to then adjust these estimates upwards as the design matures. Despite the deviations in the minima, it can be seen that the mean values for each reactor type are all within ~30% of one another. This points to the reactor type not being a statistically significant cost driver (it may prove to be in reality, but there appears to be a lack of confidence in the literature to delineate costs between reactor types).

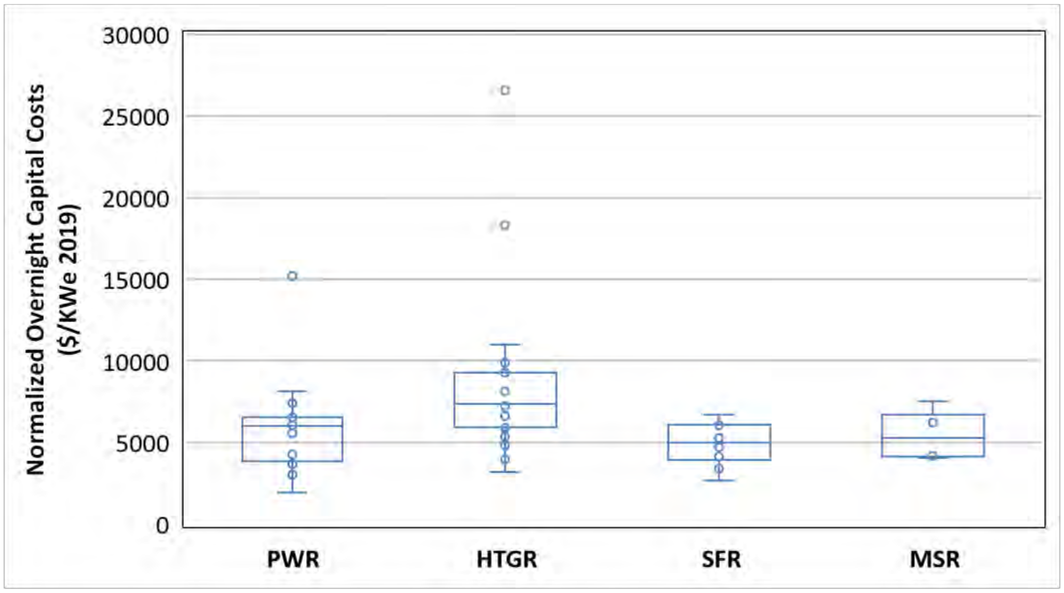


Figure 3: Whisker plot with associated standard deviations of total costs for all advanced reactors reviewed in this report.

In summary, there does not appear to be sufficient granularity in the data to be able to draw adequate conclusions regarding the variability of advanced reactor costs based on their type. As such, this study recommends using a single reference across all advanced reactors rather than attempting to discriminate between reactors. This is expected in light of the lack of 'real' data on advanced reactor costs (the literature is predominantly based on predictive estimates). As these reactors come online, differentiation between them might become more apparent (or consistent, thorough, cross-comparisons might be needed). Nevertheless, other factors (such as learning rates and the number of units per plant) are apparently impacting cost considerations. This will be investigated further in Section 2.8.

### Grouping Based on Reactor Size

The second step was to evaluate the sensitivity of reactor cost estimates on their size. To this end, reactors were grouped between: Large (> 400 MWe), SMR (50-400 MWe), and microreactor (< 50 MWe). The resulting scatter plot was updated in Figure 4 and plotted with a logarithmic x-axis to facilitate comparison within different scales (especially for microreactors). The cost estimate for microreactor Design A (72,610 $\$_{2019}$/kWe) from reference [33] is not included to better visualize clusters by reactor types and power levels. It is important to note that that particular design was intended for experimental/research application rather than commercial applications. While the datapoints are clearly clustered along the power-level (by design), their variability along the y-axis (normalized specific costs) overlaps substantially, especially for the large reactors and SMRs.

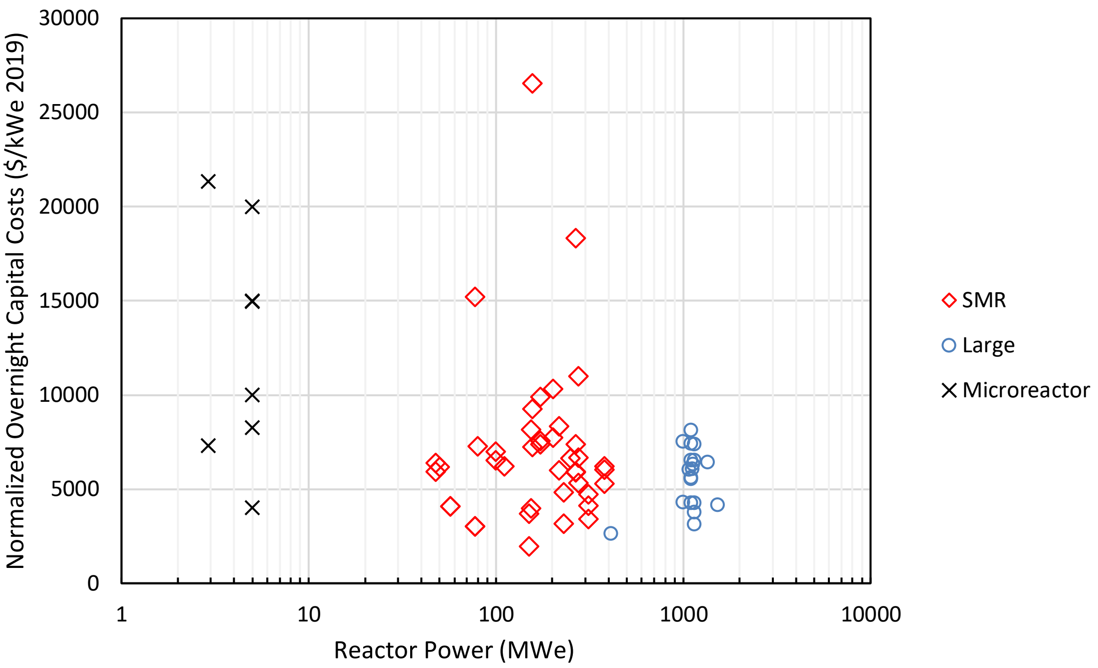


Figure 4: Scatter plot of specific costs versus reactor power rates for three sizes of nuclear reactors. Note that the x-axis here is expressed in terms of reactor unit output (not total plant output).

Upon closer inspection, this conclusion is also confirmed with the whisker plot in Figure 5. While the microreactor cost estimates appear to have substantially different costs than the other classes, limited variation between large reactors and SMRs was observed. At this stage, this literature survey did not find a significant difference in values between large reactors and SMRs. This somewhat contradicts the conclusion in [6], which seems to indicate that SMR are expected to have higher mean costs than larger reactors, but with a narrower min/max band. This can be potentially attributed to biases or inconsistencies in the various references surveyed. It is expected that the construction of large reactors would hold in more hidden costs due to delays [39], which SMRs seek to mitigate. Since the current study weighs all references equally and does not attempt to revisit all of the assumptions in the literature on advanced reactor cost evaluation, these differences between SMR and larger reactors are not immediately apparent. This could be potentially improved in future work.

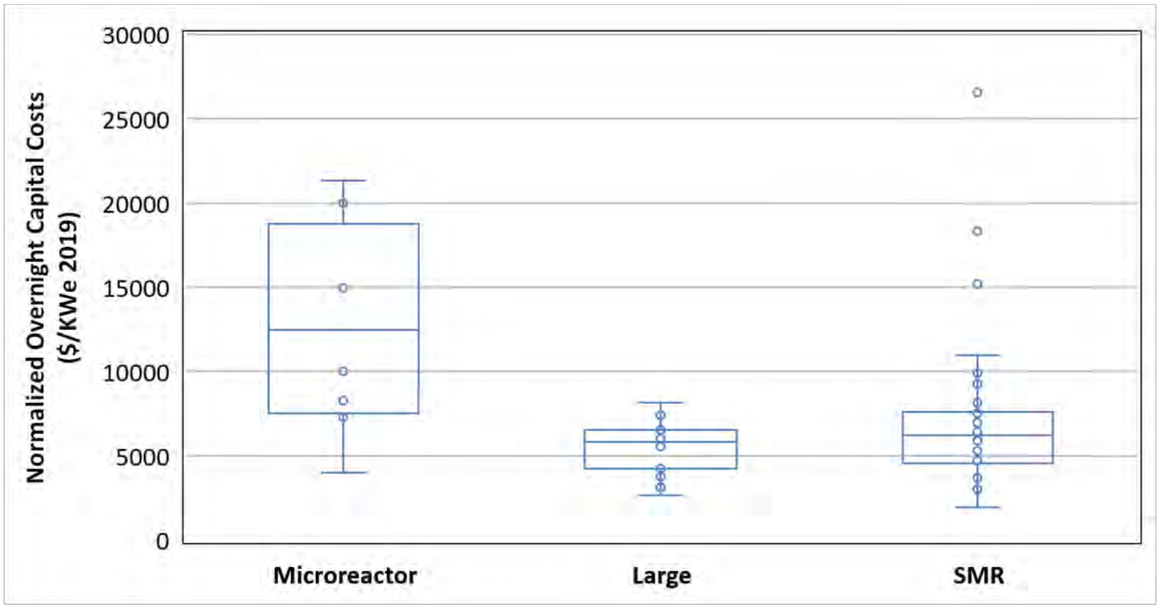


Figure 5: Whisker plot with associated standard deviations of total costs for three sizes of nuclear reactors reviewed in this report. Note that the main outliers for the SMR groupings correspond to the NGNP and NuScale FOAK estimates.

In conclusion, there appears to be no consensus in the existing literature on the impact of large versus SMR-scale reactors nor on their technology types. The only differentiation that is quantifiable at this stage is for microreactors. As such, this report will only use two groupings based on reactor types: (1) large reactors and SMRs, and (2) microreactors. This will inform the granularity in cost values in upcoming sections. However, it is important to note the noise in the data could be disentangled with further, deeper analysis, which is beyond the scope of the current literature review.

## 2.5 Tier 1 Estimates: Levelized Cost of Electricity

Based on the findings in the previous sections, values will be grouped into large and small reactors on the one-hand and microreactors on the other. The first tier in the analysis consisted of reviewing the data on LCOE. Figure 6 shows a histogram of the distribution of estimates within the literature. It illustrates the large spread in the data on LCOE for advanced reactors and the challenge with identifying specific values.

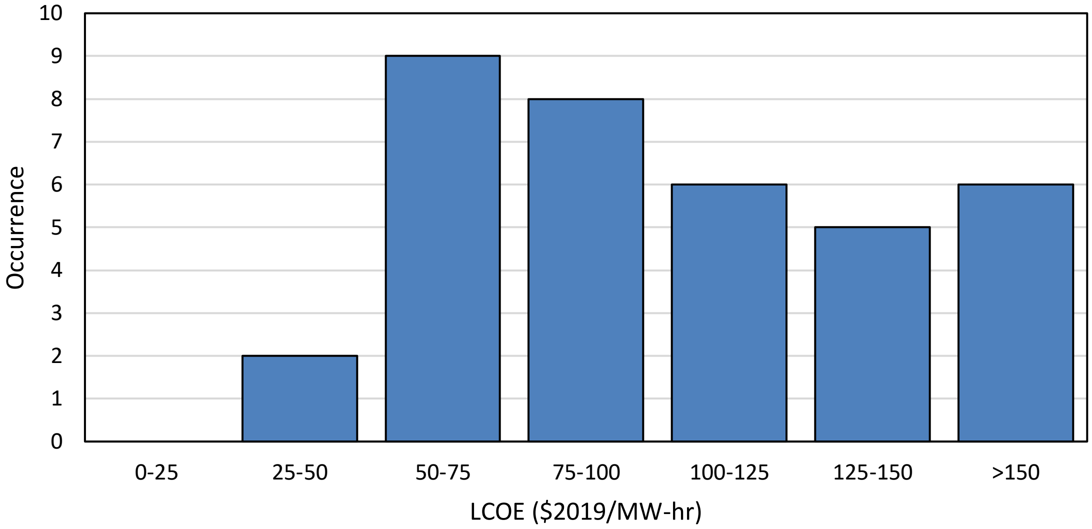


Figure 6: Histogram of LCOE values for Large and SMR (no microreactors).

Table 4 provides a statistical breakdown of the distribution shown above along with estimates for microreactors. It is important to note that this aggregate corresponds to neither FOAK nor NOAK costs, but rather a combination of both. As a result, a new term is coined here: Between first and Nth of a Kind (BOAK). This essentially represents the expected cost for early deployment of advanced reactors beyond the first demonstration. It is a helpful 'in-between' for higher-level cost evaluations.

Table 4. Advanced reactor LCOE distribution for BOAK observed in the literature review of cost estimates. Values were rounded up/down to avoid inferring more confidence in the estimates than the original data.

| | **Min** | **Q1** | **Mean** | **Q2 (Med)** | **Q3** | **Max** |
|---|---|---|---|---|---|---|
| **Large & SMR ($$_{2019}$/MW-hr)** | 43 | 64 | 107 | 92 | 133 | 367 |
| **Microreactor ($$_{2019}$/MW-hr)** | 150 | 150 | 285 | 310 | 403 | 410 |

The relatively large number of outlier data points results in a noticeable difference between the mean and median (Q2) of the dataset. Furthermore, several lone outliers push the min/max values further away than the bulk of the datapoints. As a result, for the purposes of future high-level evaluations of advanced reactor deployment potential it is recommended to use the Q2, or median, value as the reference point with the quartiles, Q1/Q3, for sensitivity evaluations. It is important to note however that LCOE estimates have proven to be a limited way of estimating overall system costs for generating electricity [2]. This tier of estimates is therefore not ideal for models that do not account for grid-level systems costs. It is primarily relevant for comparison against similar firm generation sources with equivalent $CO_2$ emissions (e.g., firm coal fired plant with carbon capture and sequestration) or models that are able to treat these sources differently.

## 2.6 Tier 2 Estimates: Overnight Capital and Operating Costs

While LCOE provides useful initial guidance on potential costs for advanced reactors, a more useful metric is a breakdown between overnight capital and operating costs (OCC and OPEX). Identified values based on the literature survey are provided for larger and microreactors in Table 5 and Table 6 respectively. Note that the estimates come with several caveats:

1. As previously explained, all datapoints in the literature were weighted equally. Hence the meta-analysis does not account for dissimilarities in assumptions etc.
2. The highlighted low/medium/high values correspond to the quartiles (1st, 2nd, and 3rd) rather than max/mean/min values. This is due to the high degree of variation in the data and outliers.
3. The resulting LCOE provided in Tier 2 does not line up directly with the values provided in Table 4. This is due to inconsistencies in the data: not all references that quoted LCOE values quoted OCC and OPEX values, and vice versa. In addition, there are discrepancies in assumptions between the various ways LCOE, OCC, and OPEX values are estimated. This led to differences in the Tier 1 versus Tier 2 estimates. Note that the Tier 2 LCOEs were estimated assuming a weighted average cost of capital of 8% (in line with utilities [40]), a reactor lifetime of 60 years (conservative as several reactors are being extended beyond this point [41]), and a capacity factor 92% [42].
4. The values quoted are for a 'BOAK' estimates. This represents a reactor between the first and Nth of a kind.

Table 5. Identified low, medium, and high estimates for total costs for small modular and large reactors cost estimates reviewed in this report. Standard deviations are also provided. All values are in 2019 USD. Note that the estimated LCOE values here do not necessarily line up with those estimated in Tier 1.

| Large & SMR | Low | Medium | High | Sd |
|---|---|---|---|---|
| **Overnight Capital costs** | $4,000 /kWe | $6,000 /kWe | $7,000 /kWe | $3,800 /kWe |
| **Operating Costs** | $15 /MWh | $25 /MWh | $35 /MWh | $15 /MWh |
| **LCOE (estimated)** | $60 /MWh | $80 /MWh | $100 /MWh | $50 /MWh |

Table 6. Identified low, medium, high estimates for total costs of total costs for microreactors cost estimates reviewed in this report. All values are in 2019 USD.

| Microreactor | Low | Medium | High | Sd |
|---|---|---|---|---|
| **Overnight Capital Costs** | $8,000 /kWe | $13,000 /kWe | $17,000 /kWe | $5,800 /kWe |
| **Operating Costs** | $70 /MWh | $100 /MWh | $135 /MWh | $30 /MWh |
| **LCOE (estimated)** | $150 /MWh | $250 /MWh | $300 /MWh | $90 /MWh |

It is important to highlight the dearth of data on microreactors. The current values are only based on two references in the literature and will need to be updated as more estimates are published. As such, the values are very approximative and care should be taken when leveraging them for microreactor-specific use cases. Additional cost estimation for microreactors is crucial to reach higher confidence in projected costs.

Figure 7 helps visualize the identified values for large reactors and SMRs within the entire dataset. It can be seen that they encapsulate the majority of datapoints. Some outliers do appear to be outside of the upper quartile bounds, these are predominantly associated with FOAK estimates which will be addressed more closely in Section 0.

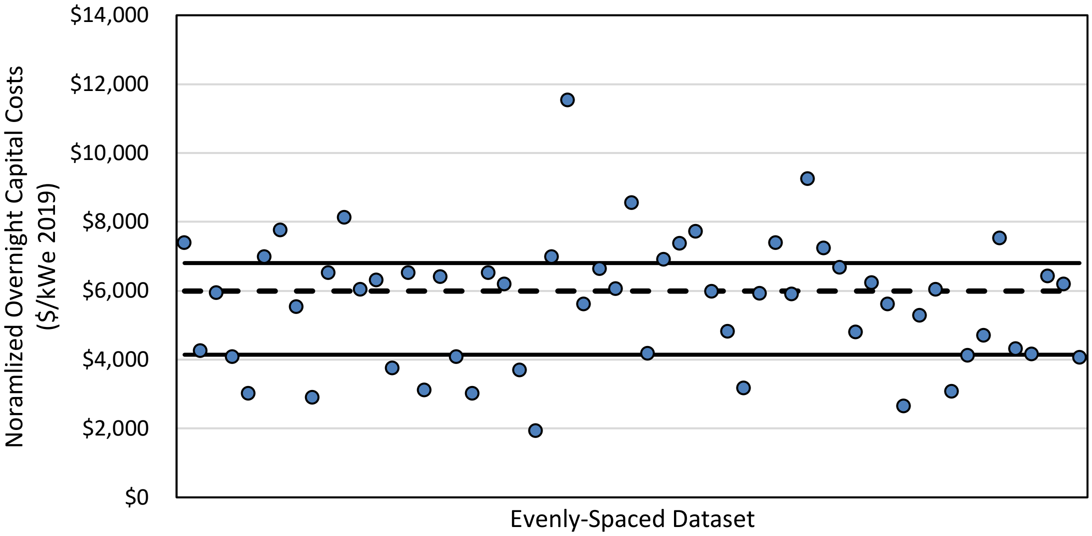


Figure 7. Distribution of the data points between the low/high (solid line) estimates. The medium estimate is shown in the dashed line.

Looking more closely, it does appear that the median (which corresponds to the ‘medium’ value) skews slightly upwards. This can be attributed to the data not following a normal distribution as shown in Figure 8, with a significant proportion of estimates within the high data ranges. The distribution does display a right tailed ‘double hump’ or bimodal distribution, each of which is likely associated with FOAK versus NOAK costs. The right-tailed nature of this distribution is expected, as projects commonly become more expensive due to significant cost overruns and delays, but a realistic limit always exists to how cheaply they can be built.

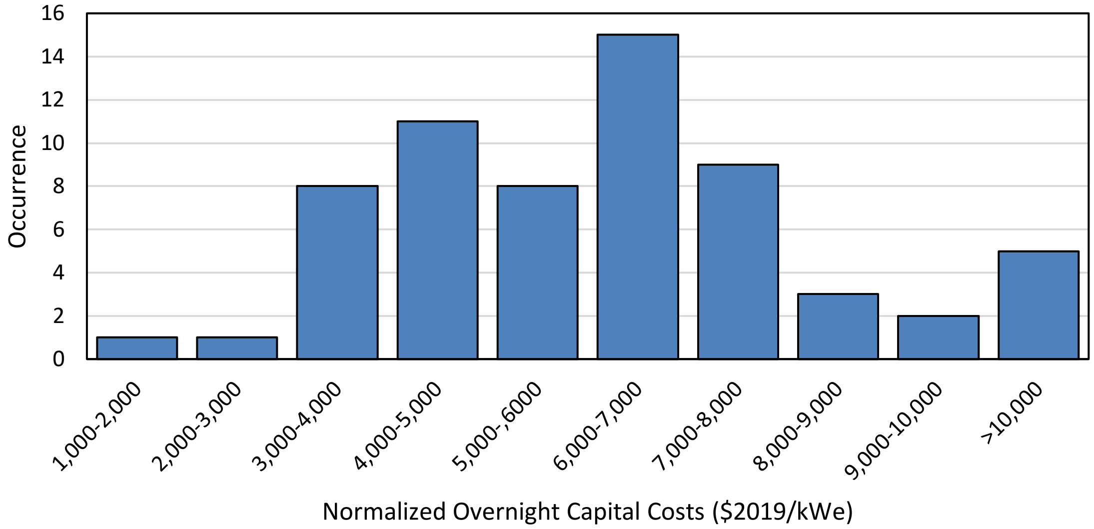


Figure 8. Distribution of the normalized overnight capital cost estimates

The evolution of the contributions of the different cost estimates is plotted in Figure 9. Looking backwards from the most recent datapoints (2022), the average and median appear to stabilize beyond 2014 (towards older estimates) where the majority of dataset is captured. Overall, the median value does not drastically vary throughout the estimates (ranges between -50% and +10% of the median value of $6,000/kWe). It can be inferred from this plot that the identified values are not strongly dependent on decades-old data. However, it should be noted that many of the more recent datasets do rely heavily on more older cost estimates.

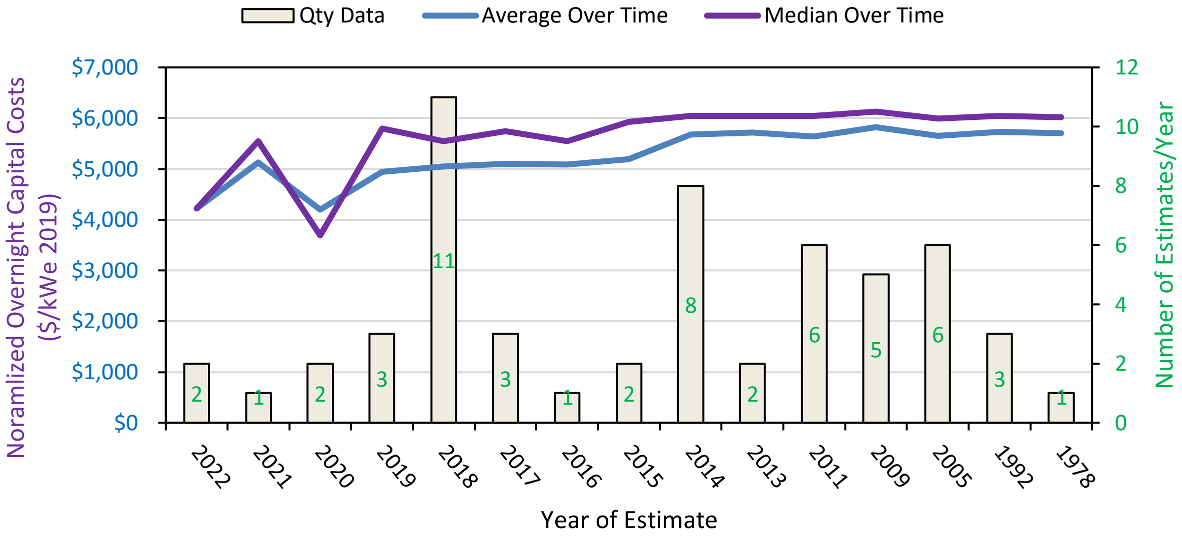


Figure 9. Contribution of the datasets (based on year) on the average and the mean overnight capital costs for large reactors and SMRs. Note this a progressive time-based aggregation and not a moving average graph.

To place the analysis in context, the identified values for large reactors and SMRs are compared to other similar meta-studies in Table 7. As can be seen, the range produced from this report intersects with the estimates for most similar meta-study highlighted. The values presented here are not anticipated to challenge the conclusions and findings of these previous analyses. It does however provide a more transparent and systematic basis for the expected cost ranges of advanced nuclear technology.

Table 7. Comparison of the identified values in this study against other meta-studies on advanced reactor cost estimates. All values are escalated to 2019 USD.

| | OCC | OPEX | LCOE |
|---|---|---|---|
| **ETI/Lucid** [24] | \$4,006/kWe | \$22/MWh | \$64/MWh |
| **MIT** [2] | \$4,100–6,900/kWe | \$11–35/MWh | \$110–120/MWh |
| **Breakthrough** [35] | \$3,018–\$7,500/kWe | \$4–23/MWh | \$31–75/MWh |
| **NIA** [43] | \$2,030–\$6,000/kWe | N/A | N/A |
| **SMR Start** [16] | \$1,846–\$3,507/kWe | \$21–28/MWh | \$40–90/MWh |
| **EIA** [15] | \$6,191/kWe | \$82/MWh | \$26/MWh |
| **PNNL** [10] | N/A | N/A | \$44–54/MWh |
| | | | |
| **This study** | **\$4,000–\$7,000/kWe** | **\$15–35/MWh** | **\$60–100/MWh** |

While the ARDP awards account for costs beyond the reactor itself, they can still provide a useful point of comparison against the identified range in this study. The X-energy award totals ~\$2.5B [44], while the Natrium ARDP is expected to cost up to \$4B [45]. This results in a normalized cost of around ~7,800$\$_{2020}$/kWe and ~\$11,600/kWe respectively, which is above the identified range for BOAK reactors in this study. This is expected since these reactors are FOAK demonstrations, and their estimates includes design, licensing, testing, fuel fabrication facility, as well as other costs. It is currently unclear if the cost estimates include the financing costs and owners' costs of the reactor(s). It should also be noted that the ARDP costs are still expected to evolve and are not finalized at this stage [4]. Because the Natrium reactor in particular has a variable power output, normalized cost comparisons are relatively challenging. Additional information on FOAK considerations to adjust the estimated values in this study is provided in Section 2.8.

## 2.7 Tier 3 Estimates: Detailed Breakdown based on Reactor Type

While OCC and OPEX costs may provide sufficient levels of granularity for grid modeling, more detailed estimates may be needed for specific evaluations of IES, especially when reactor design modifications are envisaged (e.g., separating the nuclear island from the power island using thermal energy storage). To this end, a 3rd tier of estimate is provided in this section. It is based on the Tier 2 values for OCC and OPEX, to which they are normalized. This tier will provide a detailed breakdown in percentages of various components and subcomponents that are relevant for advanced reactors.

The majority of references outlined in Section 2.2 did not provide detailed, granular information on advanced reactor types. Due to the scarcity of granular data, a single reference design was selected to represent each reactor type:

- **PWR**: The EEDB estimate for the PWR12-BE was used as the reference for this type of reactor [24]. This is often referred to as the main standard for nuclear reactor cost estimation.
- **SFR**: The cost breakdown dataset from both the ABR1000 [27] [20]. And the LSPBR (Large-Scale Prototype Breeder Reactor) [46] was leveraged to complete the full estimate for this class of reactor.
- **HTGR**: The cost breakdown from the NGNP project was used here. Specifically, the NOAK concept with 4 units, 350 MWth power output, and a 750°C outlet temperature [21].
- **MSR**: The DMSR was used as the reference for this class of reactor [31].

The information for each reactor was then organized into a 'Code of Accounts'. This provides a structured approach to capturing the various costs associated with advanced reactors. Expenses are grouped between 'accounts' each with several 'sub-accounts.' A standardized numbering structure helps reviewers understand the level of detail for a corresponding account. For instance, account number '10' is the highest level, '11' is lower, '111' is the next level, and '111.111' would be the lowest level. This structure ensures that all costs are captured and populated and provides a standardized means of comparison across various reactor types. For the purposes of this study, the Generalized Nuclear Code of Accounts (GN-COA), developed by the Systems Analysis & Integration (SA&I) program, was leveraged here [47]. It builds on previous COA in the literature but provides additional flexibility that is useful for this study. Namely, it defines accounts in terms of functional roles rather than specific technologies (e.g., 'Reactivity Control System' instead of 'Control Rods'). The resulting breakdown for each reactor category using the GN-COA is provided in Table 8. The original breakdown in costs is provided in Appendix B.

Table 8. Breakdown of the percentage contribution of each account to the total OCC (in $/kWe) of each reactor type.

| | | PWR | SFR | HTGR | MSR |
|---|---|---|---|---|---|
| 10 | Preconstruction cost | 2.35% | 5.30% | 1.19% | 2.74% |
| 11 | Land and land rights | 0.11% | 0.26% | 0.06% | 0.13% |
| 12 | Site permits | 0.45% | 1.01% | 0.23% | 0.52% |
| 13 | Plant licensing | 1.11% | 2.50% | 0.56% | 1.29% |
| 14 | Plant permits | 0.18% | 0.40% | 0.09% | 0.21% |
| 15 | Plant studies | 0.18% | 0.40% | 0.09% | 0.21% |
| 16 | Plant reports | 0.14% | 0.32% | 0.07% | 0.17% |
| 17 | Other preconstruction costs | 0.18% | 0.40% | 0.09% | 0.21% |
| 20 | Direct costs | 39.65% | 49.55% | 40.25% | 39.41% |
| 21 | Structures and improvements | 10.33% | 11.03% | 5.66% | 9.59% |
| 211 | Yardwork | 1.11% | 2.67% | 0.00% | 0.78% |
| 212 | Reactor containment building | 3.44% | 3.06% | 5.66% | 3.41% |
| 213 | Turbine room and heater bay | 1.28% | 0.92% | 0.00% | 1.07% |
| 214 | Security building and gatehouse | 0.06% | 0.01% | 0.00% | 0.00% |
| 215 | Primary auxiliary building and tunnels | 0.89% | 0.47% | 0.00% | 1.86% |
| 216 | Waste processing building | 0.75% | 1.45% | 0.00% | 0.00% |
| 217 | Fuel storage building | 0.44% | 1.06% | 0.00% | 0.00% |
| 218A | Control and diesel generator building | 1.02% | 0.61% | 0.00% | 1.00% |
| 218B | Administration Building | 0.34% | 0.08% | 0.00% | 0.33% |
| 218C | Operation and Maintenance (O&M) Center | 0.00% | 0.00% | 0.00% | 0.00% |

| | | | | | |
|---|---|---|---|---|---|
| 218C | Turbine building | 0.00% | 0.06% | 0.00% | 0.00% |
| 218D | Fire pump housing | 0.02% | 0.01% | 0.00% | 0.02% |
| 218E | Steam Generator Storage Building | 0.00% | 0.00% | 0.00% | 0.00% |
| 218 E | Emergency feed pump building | 0.12% | 0.14% | 0.00% | 0.12% |
| 218 F | Manway tunnels | 0.04% | 0.00% | 0.00% | 0.04% |
| 218 H | Non-essential building | 0.00% | 0.02% | 0.00% | 0.02% |
| 218 I | Auxiliary building | 0.02% | 0.20% | 0.00% | 0.00% |
| 218 J | Steam pipe enclosures | 0.40% | 0.00% | 0.00% | 0.39% |
| 218K | Pipe tunnels | 0.02% | 0.01% | 0.00% | 0.02% |
| 218L | Electrical tunnels | 0.00% | 0.00% | 0.00% | 0.00% |
| 218L | Technical support center | 0.03% | 0.00% | 0.00% | 0.03% |
| 218N | Maintenance Shop | 0.00% | 0.09% | 0.00% | 0.00% |
| 218P | Containment hatch and shielding | 0.01% | 0.00% | 0.00% | 0.01% |
| 218Q | Foundations for outside equipment and tanks | 0.00% | 0.00% | 0.00% | 0.00% |
| 218R | Balance of plant service building | 0.00% | 0.00% | 0.00% | 0.00% |
| 218R | Auxiliary boiler building | 0.00% | 0.02% | 0.00% | 0.00% |
| 218S | Wastewater treatment building | 0.03% | 0.01% | 0.00% | 0.03% |
| 218T | Emergency power generation building | 0.00% | 0.00% | 0.00% | 0.00% |
| 218T | Ultimate heat sink structure | 0.31% | 0.00% | 0.00% | 0.30% |
| 218T* | Interim sodium storage | 0.00% | 0.14% | 0.00% | 0.00% |
| 218V | Container room for emergency air intake | 0.00% | 0.00% | 0.00% | 0.00% |
| 218W | Warehouse | 0.00% | 0.00% | 0.00% | 0.00% |
| 218X | Railroad tracks | 0.00% | 0.00% | 0.00% | 0.00% |
| 218Y | Roads and paved areas | 0.00% | 0.00% | 0.00% | 0.00% |
| 218Z | Reactor receiving and assembly building | 0.00% | 0.00% | 0.00% | 0.00% |
| 219 | Heat stack | 0.00% | 0.00% | 0.00% | 0.15% |
| 219A | Training center | 0.00% | 0.00% | 0.00% | 0.00% |
| 219K | Special material unloading facility | 0.00% | 0.00% | 0.00% | 0.00% |
| 22 | Reactor equipment | 12.50% | 23.95% | 14.79% | 14.51% |
| 220 | Nuclear Steam Supply System (NSSS) | 6.05% | 17.07% | 5.79% | 7.30% |
| 221 | Reactor equipment | 0.38% | 0.25% | 0.83% | 0.56% |
| 222 | Main heat transport system | 0.69% | 0.33% | 0.77% | 0.56% |
| 223 | Safety systems | 0.84% | 0.06% | 0.77% | 0.52% |
| 224 | Radwaste processing | 1.04% | 2.38% | 0.97% | 0.83% |
| 225 | Fuel handling systems | 0.14% | 0.17% | 2.57% | 0.84% |
| 226 | Other reactor plant equipment | 2.26% | 0.78% | 2.07% | 2.57% |
| 227 | Reactor instrumentation and control | 0.78% | 2.45% | 0.74% | 0.82% |
| 228 | Reactor plant miscellaneous items | 0.31% | 0.46% | 0.28% | 0.51% |
| 23 | Energy conversion system (Rankine) | 8.76% | 3.88% | 9.13% | 8.16% |
| 231 | Turbine-generator | 4.58% | 1.72% | 4.84% | 3.37% |
| 233 | Condensing systems at the turbine | 1.17% | 0.73% | 1.21% | 0.99% |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| 234 | Feedwater heating system (part of the turbine) | 1.10% | 0.59% | 1.13% | 1.75% |
| 235 | Other turbine plant equipment | 1.33% | 0.46% | 1.35% | 1.53% |
| 236 | Instrumentation and control | 0.27% | 0.16% | 0.27% | 0.17% |
| 237 | Turbine plant miscellaneous items | 0.32% | 0.21% | 0.33% | 0.34% |
| 24 | Electrical Equipment | 3.92% | 5.56% | 8.11% | 4.55% |
| 241 | Switchgear | 0.40% | 0.86% | 0.87% | 0.46% |
| 242 | Station service equipment | 0.65% | 1.45% | 1.38% | 1.11% |
| 243 | Switchboards | 0.07% | 0.02% | 0.15% | 0.09% |
| 244 | Protective systems equipment | 0.17% | 0.14% | 0.35% | 0.18% |
| 245 | Electric structure and wiring | 1.55% | 1.61% | 3.14% | 1.07% |
| 246 | Power and control wiring | 1.08% | 1.48% | 2.22% | 1.63% |
| 25 | Heat rejection system | 1.85% | 3.31% | 2.56% | 1.16% |
| 251 | Structures | 0.15% | 0.10% | 0.21% | 0.11% |
| 252 | Air, water, and steam service systems | 1.70% | 3.21% | 2.35% | 1.05% |
| 26 | Miscellaneous equipment | 2.29% | 1.81% | 0.00% | 1.46% |
| 261 | Transportation and lift equipment | 0.21% | 0.13% | 0.00% | 0.24% |
| 262 | Heat rejection system mechanical equipment | 1.63% | 1.28% | 0.00% | 0.88% |
| 263 | Communications equipment | 0.24% | 0.24% | 0.00% | 0.18% |
| 264 | Furnishing and fixtures | 0.10% | 0.06% | 0.00% | 0.09% |
| 255 | Wastewater treatment building | 0.10% | 0.09% | 0.00% | 0.07% |
| 27 | Special Materials, Including Coolant | 0.00% | 0.00% | 0.00% | 0.00% |
| 28 | Simulator | 0.00% | 0.00% | 0.00% | 0.00% |
| 29 | Other capitalized direct costs | 0.00% | 0.00% | 0.00% | 0.00% |
| 30 | Indirect costs | 44.16% | 34.33% | 44.83% | 43.90% |
| 31 | Field indirect costs | 13.32% | 10.35% | 13.52% | 13.24% |
| 32 | Construction supervision | 12.42% | 9.66% | 12.61% | 12.35% |
| 33 | Commissioning and startup costs | 0.59% | 0.46% | 0.60% | 0.58% |
| 34 | Demonstration test run | 0.00% | 0.00% | 0.00% | 0.00% |
| 35 | Design services offsite | 15.37% | 11.95% | 15.60% | 15.28% |
| 36 | PM/CM services offsite | 0.74% | 0.58% | 0.75% | 0.74% |
| 37 | Design services onsite | 0.67% | 0.52% | 0.68% | 0.66% |
| 38 | PM/CM Services onsite | 1.06% | 0.82% | 1.07% | 1.05% |
| 40 | Owner costs | 12.57% | 9.77% | 12.76% | 12.50% |
| 41 | Staff recruitment and training | 3.14% | 2.44% | 3.19% | 3.12% |
| 42 | Staff housing | 3.14% | 2.44% | 3.19% | 3.12% |
| 43 | Staff salary-related costs | 3.14% | 2.44% | 3.19% | 3.12% |
| 44 | Other owner’s costs | 3.14% | 2.44% | 3.19% | 3.12% |
| 50 | Supplementary costs | 1.28% | 1.05% | 0.96% | 1.45% |
| 51 | Shipping and transportation costs | 0.18% | 0.15% | 0.16% | 0.21% |
| 52 | Spare parts | 0.18% | 0.15% | 0.16% | 0.21% |
| 53 | Taxes | 0.18% | 0.15% | 0.16% | 0.21% |

| | | | | | |
|---|---|---|---|---|---|
| 54 | Insurance | 0.18% | 0.15% | 0.16% | 0.21% |
| 55 | Initial fuel core load (capitalized) | 0.00% | 0.00% | 0.00% | 0.00% |
| 58 | Decommissioning costs | 0.57% | 0.44% | 0.34% | 0.62% |

As highlighted previously, a mix of different references was used in several instances to populate these cost breakdowns. For instance, the preconstruction costs are assumed to be independent of reactor types, and the same values are used for the PWR-12, ABR1000, and DMSR. This is because the detailed estimations are missing in the reference, and data in EEDB for PWR are considered main standards for nuclear costs. These estimates are obtained from reference [48], which assume a 2-year land acquisition and plant license. The preconstruction costs for NGNP are estimated based on the total preconstruction costs in [21] and mappings in [48]. The overnight capital costs of PWR and DMSR are collected from [48]. The overnight capital costs of ABR1000 are obtained by combining several datasets in reference [27] with reference [48]. The overnight capital costs of HTGR are obtained by combining reference [21] and [48].

The next step is to provide a detailed breakdown of the contribution to OPEX costs of the reactors. This is provided separately since the units are expressed in $/MWh instead of $/kWe. Similarly, the data is structured via the GN-COA framework, and percentage contributions of each account are summarized in Table 9. The estimates are extracted from reference [48].

Table 9. Breakdown of the percentage contribution of each account to the total OPEX (in $/MWh) of each reactor type.

| | | **PWR** | **SFR** | **HTGR** | **MSR** |
|---|---|---|---|---|---|
| 70 | Operating Staff Costs | 95.98% | 58.14% | 55.62% | 98.18% |
| 71 | O&M staff | 35.54% | 24.61% | 20.21% | 30.12% |
| | Onsite O&M staff | 21.77% | 17.70% | 12.27% | 12.58% |
| | Offsite technical support | 13.77% | 6.90% | 7.94% | 17.54% |
| 72 | Management staff | 20.90% | 13.70% | 12.62% | 17.68% |
| | Onsite management staff | 10.34% | 8.41% | 6.53% | 4.23% |
| | Other admin and general expenses | 10.56% | 5.29% | 6.09% | 13.45% |
| 73 | Salary-related costs | 9.63% | 4.83% | 5.55% | 12.27% |
| 74 | Operating chemicals and lubricants | 0.00% | 0.00% | 0.00% | 0.00% |
| 75 | Spare parts | 0.00% | 0.00% | 0.00% | 0.00% |
| 76 | Utilities, supplies, and consumables | 23.40% | 11.73% | 13.49% | 29.81% |
| 77 | Capital plant upgrades | 0.00% | 0.00% | 0.00% | 0.00% |
| 78 | Taxes and insurance | 6.52% | 3.27% | 3.76% | 8.31% |
| 80 | Annualized fuel cost | 4.02% | 41.86% | 44.38% | 1.82% |
| 81 | Refueling operations | 0.00% | 0.00% | 0.00% | 0.00% |
| 84 | Nuclear fuel | 2.01% | 29.46% | 35.16% | 0.51% |
| 86 | Fuel processing charges | 2.01% | 12.40% | 9.22% | 1.31% |
| 87 | Special Nuclear Materials | 0.00% | 0.00% | 0.00% | 0.00% |

The resulting distribution of the contributions of various accounts to the total OCC is plotted in Figure 10. They are ranked in terms of highest contribution to the PWR reference costs. The plot helps identify the main cost drivers for the different reactor designs. Notably, for PWRs (PWR-12), HTGR (NGNP), and MSR (DMSR), Account 35: design services offsite, is the largest (15.35% for PWR-12, 15.60% for NGNP, 15.42% for DMSR) capital cost contributor. For SFR (ABR-1000), account 220: nuclear steam supply system (NSSS) is the major contributor (17.07%). The variability between reactor types illustrates the need for this 3rd tier of detailed costs breakdown when evaluating different reactor technology types.

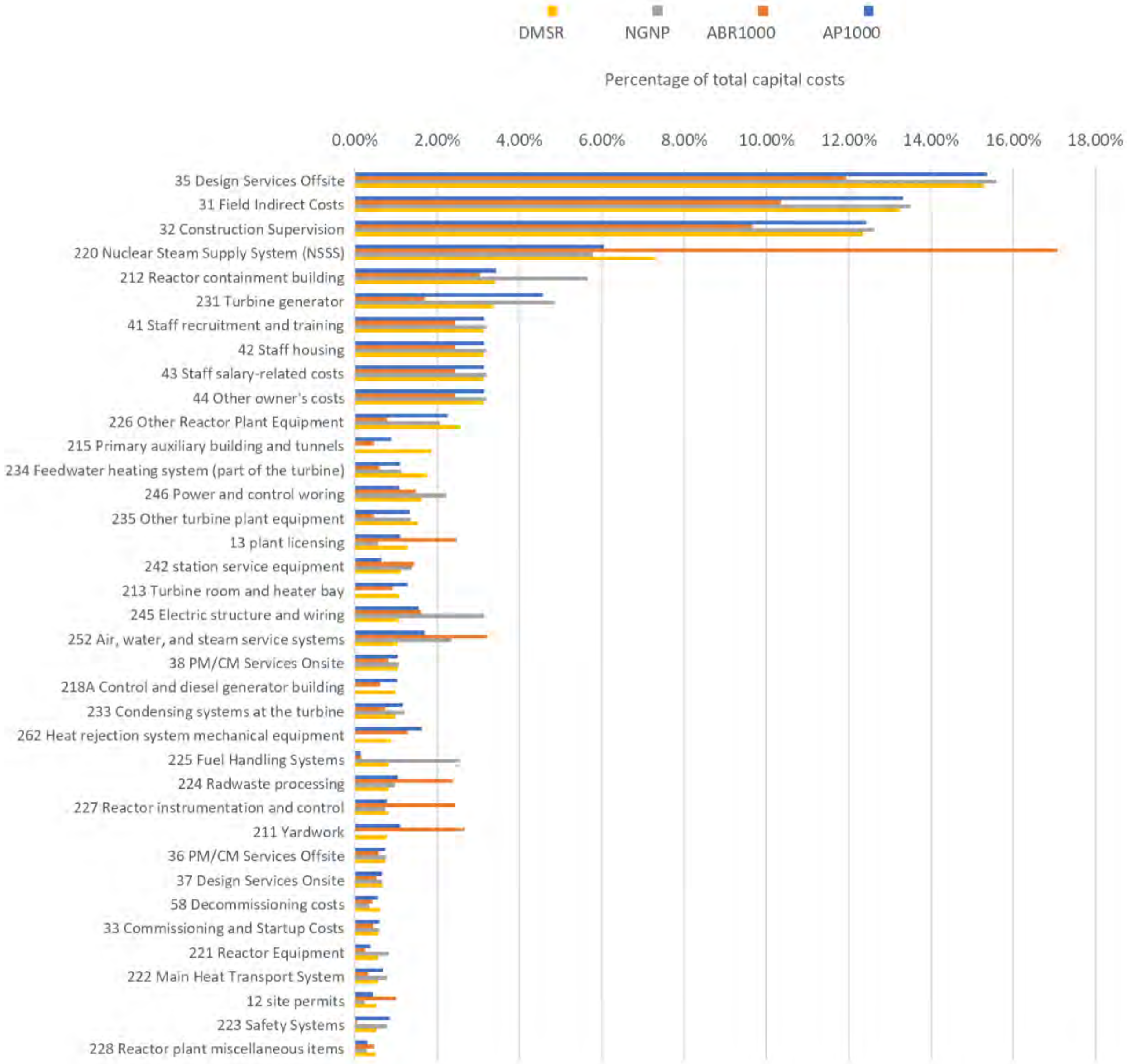


Figure 10: Percentage contribution of each account to total direct costs. Accounts are ranked in order of highest contribution to the PWR COA.

## 2.8 Recommended Cost Adjustments

The type of reactor was not observed to conclusively drive overall cost estimates for both the OCC and OPEX of advanced reactors (the type does however have an impact on lower-level cost accounts contribution to the total cost). Several other factors, however, can substantially influence reactor costs. This section does not attempt to quantify the impact of all factors but chooses instead to focus on three specific items: (1) the premiums associated with FOAK, (2) the impact of learning rates, and (3) the impact of multi-unit plants. For each of these three parameters, *cost adjustments* are suggested here to enable more nuanced analyses. Additional cost contributors are discussed briefly in Section 3.3, without providing quantitative adjustments.

### FOAK Premium

The identified values for the Tier 2 estimates in Section 2.6 were for BOAK reactors. FOAK demonstrations are likely to incur substantially higher cost of deployment. Several of the references in the literature surveyed in this study provided cost estimates for both FOAK and NOAK reactors. The ratios of FOAK to BOAK were identified and provided in Table 10. The first column indicates the reactor type and the references for FOAK costs. The second column shows the FOAK to BOAK ratios. These values were obtained by escalating all FOAK costs to the reference 2019 USD. Then each FOAK estimate was manually correlated with a corresponding BOAK quartile (flagged in this report as low, medium, high) from Table 5. The BOAK quartile that most closely aligned between the FOAK and NOAK value for a given reactor type was then used as the ratioed against the FOAK value.

Table 10. Ratio of FOAK to BOAK cost estimates in the literature reviewed.

| **Reactor** | **FOAK to BOAK Ratio** |
|---|---|
| NuScale iPWR [5] | 1.5 [6]<br>2.2 [8] |
| PWR 12 [17] [20] | 1.2 [17]<br>1.6 [20] |
| AP1000 [17] [18] | 1.2 [17]<br>1.4 [18] |
| NGNP [21] | 3.8 (350MWth) [21]<br>2.6 (600MWth) [21] |
| HC-HTGR [22] | 1.2 [22] |
| MHTGR [23] | 1.6 (SC version) [23]<br>1.7 (GT/IC version) [23]<br>1.4 (GT/DC version) [23] |

These values show the large range of potential ‘premiums’ associated with FOAK constructions. The data was split into 1st 2nd and 3rd quartiles to produce the low (1st) medium (2nd) and high (3rd) range shown in Table 11. The FOAK value can then be inferred by multiplying the identified values in Table 5 with the range of premiums. In essence, it is recommended to assume a cost escalation of 30%–110% for FOAK-type demonstration projects.

$$FOAK = BOAK \times Premium \tag{2}$$

Table 11. Identified range of BOAK to FOAK premiums for cost adjustment.

| | **Low** | **Medium** | **High** |
|---|---|---|---|
| **BOAK to FOAK Premium** | 1.3 | 1.6 | 2.1 |

When adjusting costs to obtain FOAK estimates, it is important to be aware of potential correlations in the data when selecting which of the low/medium/high numbers to choose from. With this in mind, it is not necessarily recommended that one assign high FOAK premiums to high BOAK costs as this could produce an overly conservative estimate. Pairs of FOAK premiums with BOAK costs should be carefully considered to produce realistic FOAK costs. In general, the medium value is recommended across the cost range for BOAK estimates and deviation from this should be deliberate.

## Learning Rates

While a FOAK demonstration would increase cost estimates for nuclear reactors, learning rates are expected to substantially reduce costs over time. Serial construction/manufacture of advanced reactors is widely expected to result in better practices that lead to lower costs. A FOAK demonstration may have unexpected cost increases arising from factors such as development costs, incomplete designs, supply chain issues, or licensing/regulatory compliance challenges. As a result, FOAK costs are not fully reflective of the full economic benefits of a design. This would especially hold true in countries such as the United States where few reactors have been constructed in the recent decades.

As more reactors are built, lessons learned from those previously built are incorporated and uncertainties are reduced. Figure 11 illustrates the progressive evolution in costs going from the FOAK (and before—even at the R&D stage) to the NOAK. Non-recurring deployment costs incurred for the FOAK plant are also highlighted. This includes generic design and licensing costs that are not incurred beyond the FOAK plant.

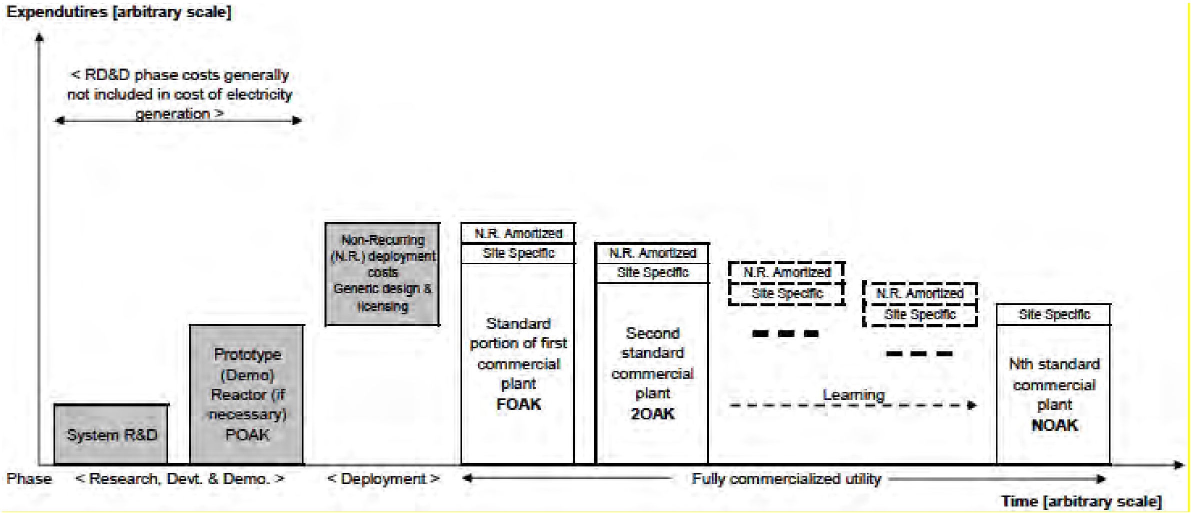


Figure 11. Temporal relationship between early stage of reactor deployment activities to NOAK level costs. Taken from [49].

Various economic analyses have attempted to estimate the reduction in costs in nuclear power plant via learning [47] [50] [51] [52]. All of these studies quantify the reduction in costs from FOAK to NOAK via ‘learning rates’. These are defined as the percentage reduction in cost when a doubling in number of deployments is achieved [53] [54]. For example, a learning rate of 5% implies that the cost of the second plant will be 95% that of the FOAK, and the 4th plant will be 90.25% (95% of 95%) and so on. Mathematically this can be expressed as:

$$Cost_N = FOAK \times (1 - LR)^{\log_2 N} \tag{3}$$

Where $LR$ is the learning rate assumed for a given reactor concept. The value is typically calculated using experience and statistical analysis of past data. Due to the lack of data on advanced reactor power plant builds in the United States, researchers have inferred learning rates values based on observed learning in similar industries. Reference [35] provides a useful literature review of learning rates relevant to advanced reactors. Based on these estimates, low/medium/high learning rate values are suggested in Table 12.

Table 12. Identified learning rate range.

| | **Low** | **Medium** | **High** |
|---|---|---|---|
| **Learning Rate (LR)** | 5% | 10% | 15% |

## Multi-unit Correction

Most advanced reactors are being designed to be smaller to enable modularization and standardization. Building large plants with SMRs involves installing multiple reactors in the same plant with a common balance of plant and other shared components, depending on the design. Multi-unit LWR plants already exist in the United States. Multi-unit plants have lower balance of plant (BOP) costs per unit of electricity generated, but more significantly, they are known to have lower O&M costs. This is due to the pooling of infrastructure and resources between several units at the same site. For instance, a single auxiliary building can support several reactors instead of one. Maintenance staff can also rotate between reactors with outages scheduled in a staggered fashion. Therefore, when evaluating the levelized cost of advanced reactors and SMRs this is a key aspect that affects both overnight capital and annual costs.

Reference [21], which provides cost estimates for an HTGR in the NGNP project, was leveraged to estimate OCC and OPEX reductions in multi-unit plants. In that reference, the OCC was separated between: (1) plant without power cycle (i.e., COA 23), (2) cost of a Brayton cycle only, and (3) cost of a Rankine cycle only. An exponential function shown in Equation 4 below was used to evaluate the OCC of the four-unit plant from the OCC (irrespective of the type of thermal cycle) of the one-unit plant with the number of units as 4.

$$OCC_n = \frac{1}{n} \times OCC_{1\,unit} \times (n)^{MUE} \tag{4}$$

The OCC is expressed as a function of the number of units in the plant, $n$.For the plant without power cycle, a multi-unit exponent (MUE) of 0.827 was derived from several cost estimations. For the Brayton cycle and Rankine cycle costs, the exponents 0.92 and 1.0 were assumed. Therefore, the total OCC of the plant (which would be OCC of the plant without power cycle + OCC of a Brayton or Rankine cycle) would be as follows.

$$OCC_{4-unit\ Brayton\ cycle\ plant} = OCC_{1-unit\ (no\ power\ cycle)} \times 4^{0.827} + OCC_{1-unit\ (Brayton\ cycle)} \times 4^{0.92} \quad (5)$$

$$OCC_{4-unit\ Rankine\ cycle\ plant} = OCC_{1-unit\ (no\ power\ cycle)} \times 4^{0.827} + OCC_{1-unit\ (Rankine\ cycle)} \times 4^{1.0} \quad (6)$$

While these equations are not exponential, an exponential curve can be fitted while substituting the OCC in Equations 5 and 6 with the estimates in reference [21]. This results in exponents of 0.82 and 0.84 for the Brayton cycle and Rankine cycle plants, respectively. Given these exponents, an MUE in the range 0.8–0.85 is suggested.

On the OPEX side, substantial information can be inferred from the existing LWR fleet in the United States [55]. In one analysis performed by [55], single-unit LWR plants in the United States had an average O&M cost of $26.33/MWh, whereas the multi-unit LWR plants had an average O&M cost of $16.43/MWh (38% lower). Hence a simple multiplication factor is recommended to adjust operating costs of advanced reactors:

$$OPEX_{multi\ unit} = OPEX_{1\ unit} \times MOM \quad (7)$$

The resulting low/medium/high value for the multi-unit OCC exponent and OPEX multiplier are shown in Table 13. The OCC exponent estimates are based on data from [21], while the OPEX exponent range is based on data from existing LWRs [55]. These adjustment factors can be leveraged to provide rough corrections to nuclear power plant costs based on the number of units at a given site.

Table 13. Multi-unit multiplier cost adjustment ranges.

| | **Low** | **Medium** | **High** |
|---|---|---|---|
| **Multi-unit OCC Exponent (MUE)** | 0.800 | 0.825 | 0.850 |
| **Multi-unit OPEX Multiplier (MOM)** | 0.500 | 0.624 | 0.700 |

# 3. DISCUSSION AND IMPROVEMENTS

## 3.1 User Guide on Leveraging Identified Values

An important goal of this report is to identify useful cost values for advanced reactors. Figure 12 illustrates the key steps in order to obtain a granular cost estimate from this report. In practice, an end-user may be satisfied with the results from step 1 and would not need to further manipulate the data. However, if needed, this section will summarize the key identified values and how they can be leveraged to develop a basis for a cost estimate.

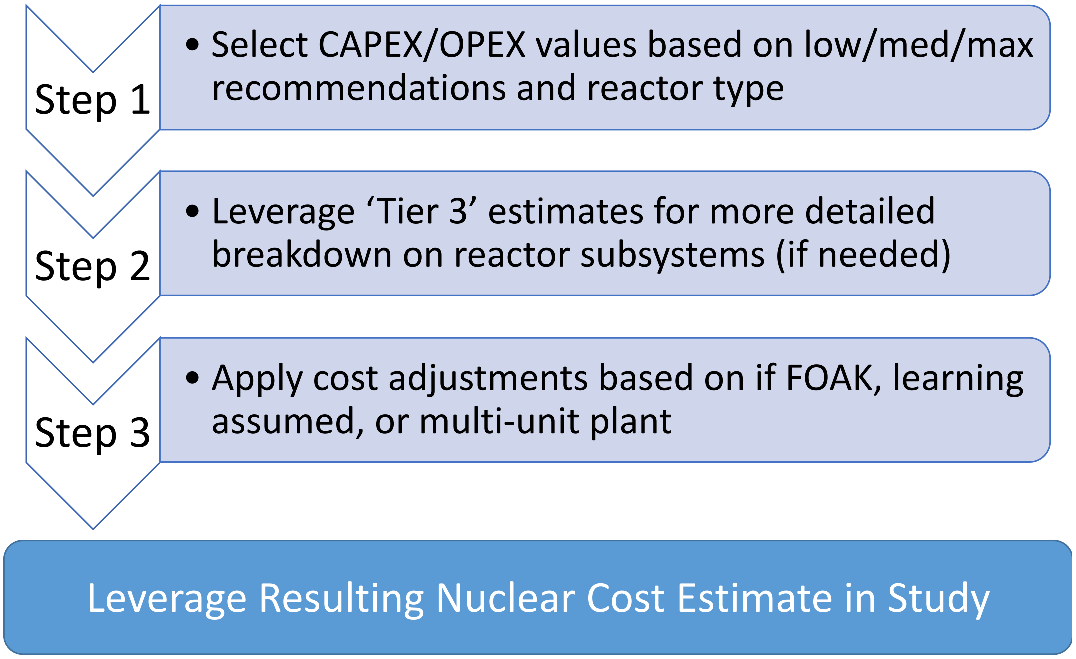


Figure 12. Illustration of the different steps to obtain nuclear reactor cost estimate for potential studies.

Several of the identified values in Section 2.6 are provided in ranges. Table 14 explains the basis for selecting between low/medium/high estimates based on a corresponding set of assumptions. The selected value would primarily depend on the type of analyses a user is planning to perform. A sensitivity study for instance, would require selecting the low/high values as a range. A simplistic capacity expansion model with few assumptions might only need the medium estimates for OCC/OPEX. A more detailed nodal model may use those same values but adjust them based on FOAK, learning, and multi-unit plant considerations. If a particular user is looking for bounding cases, low OCC/OPEX should be matched with high learning rates, and higher OCC/OPEX should be matched with lower learning rates. The medium value for FOAK is recommended in such bounding analysis, but separate sensitivity studies on FOAK costs could leverage the low/high ends. The general intent is to provide users with more granularity on nuclear costs based on assumptions and requirements of the considered use case. Note that multi-unit factors are better suited for nodal evaluations rather than capacity expansion models where specifics at a given location are not accounted for. Also note that the low value typically results in lower nuclear costs, with the exception of learning rates (low learning would result in higher costs), and vice versa for estimates marked as 'high'.

Table 14. Decision matrix based on potential assumptions in a user's model.

| | **Low** | **Medium** | **High** |
|---|---|---|---|
| **Tier 2 OCC/OPEX** | User is seeking an aggressive nuclear deployment scenario or is assuming several units have already been deployed prior to the study. | User requires a single estimate (without account for sensitivities). | Assumes a conservative cost estimate for a BOAK reactor. |

|  | Low | Medium | High |
|---|---|---|---|
| **FOAK premium*** | FOAK reactor design is assumed to be close to complete (>90%) and uncertainties for deployment are low (e.g., established technology). Unlikely to be applicable to low BOAK values. | FOAK reactor without assuming optimistic nor pessimistic assumptions for reactor deployment. | Pessimistic cost escalations with a FOAK demonstration (e.g., similar to the current experience with AP-1000). Unlikely to be applicable to high BOAK values. |
| **Learning Rate*** | Assumes minimal learning is achieved as more reactors are deployed. This is particularly suitable for reactors that are non-standardized, very site-dependent, and predominantly stick-built at the site. Unlikely to be applicable to high BOAK values. **Note:** a low value here would lead to higher end costs. | Recommended as a nominal value if the user does not want to make any underlying assumptions on how optimistic or pessimistic cost reductions occur. | Assumes aggressive learning with each reactor built. This can be particularly applicable if the reactor design is assumed to be modular and have a high fraction of activities conducted within a factory setting. Unlikely to be applicable to low BOAK values. **Note:** a high value here would lead to lower end costs. |
| **Multi-unit Factors*** | Suitable if the reactors are not expected to pool many resources and infrastructure. | User does not want to make any assumptions on the number of resources or infrastructure pooled between units. | Units pool an extensive number of resources (e.g., single control room for several reactors) and infrastructure (e.g., single turbine for many units). |

** It should be noted that because this study strives to provided projected ranges for values, users of the data should be deliberate when picking how to match or apply values from different ranges together. For example, pairing the most conservative learning rates with the most conservative cost estimates may not be a realistic assumption. Furthermore, it may be possible that conservative cost estimates receive high learning rates because these projects have fundamentally more room for learning. It is critical that users carefully considering the implications of such combination of adjustment factors.*

The main values expected to be useful for users are summarized in Table 15. Based on the decision matrix in Table 14, a user can select options that fit their use case and assumptions. Note that for heat applications, the MWth output would need to be back calculated based on the efficiency of a given reactor (typically ~30% for PWR and ~40% for HTGRs, etc.). More detailed breakdown of the percentage contribution of various costs to the OCC/OPEX is shown in Table 16. As previously explained, these values can be used for more granular assessments that are reactor specific.

Table 15. Summary of identified BOAK cost estimation values and correction factors for large reactors and SMRs.

| Variable | Low | Medium | High |
|---|---|---|---|
| **OCC** | $4,000 /kWe | $6,000 /kWe | $7,000 /kWe |
| **OPEX** | $15 /MWh | $25 /MWh | $35 /MWh |
| | | | |
| **FOAK Premium** | 1.3 | 1.6 | 2.1 |
| **Learning Rate** | 5% | 10% | 15% |
| **Multi-unit OCC Exponent** | 0.8 | 0.825 | 0.850 |
| **Multi-Unit OPEX Multiplier** | 0.5 | 0.624 | 0.7 |

Table 16. Higher-level breakdown of percentage contributions to OCC and OPEX costs based on reactor type.

| | | PWR | SFR | HTGR | MSR |
|---|---|---|---|---|---|
| **Overnight Costs** | | | | | |
| **10** | **Preconstruction Costs** | 2.35% | 5.30% | 1.19% | 2.74% |
| **20** | **Direct Costs** | 39.65% | 49.55% | 40.25% | 39.41% |
| **21** | **Structures and Improvements** | 10.33% | 11.03% | 5.66% | 9.59% |
| **22** | **Reactor Equipment** | 12.50% | 23.95% | 14.79% | 14.51% |
| **23** | **Energy Conversion System** | 8.76% | 3.88% | 9.13% | 8.16% |
| **24** | **Electrical Equipment** | 3.92% | 5.56% | 8.11% | 4.55% |
| **25** | **Heat Rejection System** | 1.85% | 3.31% | 2.56% | 1.16% |
| **26** | **Miscellaneous Equipment** | 2.29% | 1.81% | 0.00% | 1.46% |
| **30** | **Indirect Costs** | 44.16% | 34.33% | 44.83% | 43.90% |
| **40** | **Owner Costs** | 12.57% | 9.77% | 12.76% | 12.50% |
| **50** | **Supplementary Costs** | 1.28% | 1.05% | 0.96% | 1.45% |
| **Annualized Costs** | | | | | |
| **70** | **Operating Staff Costs** | 95.98% | 58.14% | 55.62% | 98.18% |
| **80** | **Annualized Fuel Costs** | 4.02% | 41.86% | 44.38% | 1.82% |

## 3.2 Example Walkthroughs for Users

To illustrate how the insights of this report can be leveraged, two example use cases are provided here. The first considers a generic plant with a specific power level and several units considered at the same site. The second example is an HTGR use case generating heat-only.

### Generic Multi-Unit Plant Evaluation

The first example considers a generic advanced reactor (unspecified) to be deployed in units. Each unit is assumed to provide 720 MWe (this can be in the form of one reactor or several). The purpose of the study is to assess the cost of the 1st, 2nd, and 3rd unit deployed. Only a medium value is needed (no sensitivity), and the use case is assumed to occur after the FOAK demonstration of the reactor.

The starting point for this is Table 5. The BOAK medium estimate can be directly leveraged to estimate the resulting capital and yearly operating expenses for the hypothetical reactor (multiplying by the total electric power output):

| | |
|---|---|
| **Unit 1 Cost** | Capital: \$4.3B<br>Operating: \$160M/year |

Note that values are purposefully rounded to avoid the inference of more precision than the underlying identified values. This practice should be applied to all manipulations of the cost inputs.

To then estimate the cost of the second and third unit, two adjustments are applied. The first is based on learning. Here we assume a medium learning of 10%, resulting in the second- and third-unit capital calculated by:

$$Unit\ 2 = BOAK\ \times\ (1 - 0.1)^{\log_2 2} = \$3.9\text{B}$$

$$Unit\ 3 = BOAK\ \times\ (1 - 0.1)^{\log_2 3} = \$3.7\text{B}$$

Then assuming a medium multi-unit exponent (0.825), the overnight cost can be adjusted using:

$$Unit\ 2 = \frac{1}{2} \times \$3.9\text{B} \times (2)^{0.825} = \$3.4\text{B}$$

$$Unit\ 3 = \frac{1}{3} \times \$3.7\text{B} \times (3)^{0.825} = \$3.2\text{B}$$

Similarly, the O&M costs for units two and three can be adjusted using:

$$O\&M_2 = O\&M_3 = O\&M_1 \times 0.624 = \$98.4\text{M}$$

Therefore, the overnight and operating cost for the two new units can be expressed as:

| | |
|---|---|
| **Unit 2 Cost** | Capital: \$3.4B<br>Operating: \$100M/year |
| **Unit 3 Cost** | Capital: \$3.2B<br>Operating: \$100M/year |

### Non-Electric HTGR Plant

In this use case, the user requirements are defined as follows:

- A gas-cooled reactor providing heat for industrial applications.
- No electricity is generated at the plant.
- The plant is a FOAK.
- No specifications of the reactor are assumed.

- An uncertainty quantification is of interest.
- The study wants to then consider potential cost reductions from learning after 10 units are deployed.

Based on these assumptions, the starting point for the analysis would be to extract the OCC/OPEX values from Table 5. In a stepwise fashion the costs for the first unit can be determined:

1. Since a sensitivity analysis is required, the full range of OCC costs will be used: [\$4,000–\$7,000]/kWe.
2. OPEX costs will range between [\$15–\$35]/MWh.
3. Since no electricity conversion is needed at the plant, the contributions of those costs can be subtracted from the range (calculation below). The resulting range narrows to [\$3,640–\$6,370]/kWe.

$$OCC_{no\ turbine} = OCC \times (1 - turbine\%) = [4{,}000 - 7{,}000] \times (1 - 0.09)$$

4. Since the application is for no-heat it is more helpful to express costs in terms of kWt. Assuming a thermal efficiency of 40%, the resulting overnight capital range becomes: [\$1,456–\$2,548]/kWt. Similarly, the operating costs can be converted to [\$6–\$14]/MWt-h

$$OCC_t = OCC_e \times \eta = [\$3{,}640 – \$6{,}370]/\text{kWe} \times 0.4$$

5. Next a FOAK premium multiplier will be applied here. Again, since a sensitivity analysis is needed here, the low and high values will be applied for each use case. The resulting OCC range expands to [\$1,892–\$5,350]/kWt.

$$FOAK = OCC \times Premium =: [\$1{,}456 – \$2{,}548] \times [1.3 - 2.1]$$

| | |
|---|---|
| **FOAK Cost** | Normalized OCC: [\$2,000–\$5,500]/kWt<br>Operating: [\$6–\$14]/MWt-h |

Note again that it is recommended to round the values so as to not infer a higher precision than the original numbers leveraged for this evaluation. Some of the higher precision numbers are still shown here to help provide a user with a reference calculation to verify against.

Finally, the impact of learning needs to be assessed. Here, the mean learning rate value of 10% is applied to both ends of the values estimated (using the high learning rate with the low estimate produces unjustifiably low-cost estimates). The calculation is conducted as follows:

$$10OAK_{high} = FOAK_{high} \times (1 - LR)^{\log_2 N} = 5{,}350 \times (1 - 0.1)^{\log_2(10)}$$

$$10OAK_{low} = FOAK_{low} \times (1 - LR)^{\log_2 N} = 1{,}892 \times (1 - 0.1)^{\log_2(10)}$$

The resulting 10th of a kind (10-OAK) values are shown below. OPEX are assumed to be constant across all units.

| | |
|---|---|
| **10-OAK Cost** | Normalized OCC: [\$1,500–\$4,000]/kWt<br>Operating: [\$6–\$14]/MWt-h |

## 3.3 Additional Cost Considerations

Nuclear power plant capital costs are influenced by a variety of design parameters. In order to estimate the overnight capital costs of advanced reactor plants that are yet to be built, it is important to identify and quantify these parameters as much as possible. In most cost studies in the literature, the commonly considered parameters are reactor size (or power capacity) and reactor technology type. In these studies, plants are pooled into ranges of reactor size, for example, large reactors, SMRs, and microreactors. When reactor technology type is considered, reactors are generally pooled into LWRs, GCRs or HTGRs, SFRs, MSRs, etc. These classifications are adequate for a rough order of magnitude (ROM), top-down cost estimation when details of the reactor or plant design are not yet available. However, they do not capture the many factors that influence cost. For example, many advanced reactor developers are using innovative techniques and design choices with the goals of reducing cost, shortening construction timeline, and minimizing overall project risk. When implemented, these techniques and design choices can have a significant impact on cost, potentially a larger impact than just choosing a certain reactor technology. Some of these techniques are described below with examples. However, this list is not exhaustive (and the techniques are not mutually exclusive), and other approaches are also being currently pursued for cost reduction of advanced reactor power plants.

### Learning

In the review presented in this report, as well as across the literature, overnight capital costs are typically presented as FOAK or NOAK costs. The primary difference between the FOAK and NOAK costs is the degree of learning. As more and more plants or plant components are built on site or in a factory, the experience gained increases efficiency and quality, and reduces risk of cost and schedule overruns. The impact of learning on cost is quantified using learning rate, which is defined as the percentage reduction in unit cost for every doubling of cumulative production. That is, with a learning rate of 10% or 0.10, the second plant will be 10% cheaper than the 1st plant, the 4th plant will be 10% cheaper than the 2nd, and so on (assuming that the plants are built consecutively without a significant delay between their construction).

Typically, learning rates are positive (negative learning rates have been observed in the United States due to regulatory changes in the 1980s following the incident at Three Mile Island [36] due to increased requirements), and as more plants are built, the cost decreases. Learning rates are calculated from historical cost data and can be applied for any COA, if supported by the data. Although the estimated FOAK costs of advanced reactors and SMRs might be high, since they are being designed to be modular and supported by offsite factory fabrication, they are expected to have good learning rates and therefore, make a faster transition from FOAK to NOAK costs.

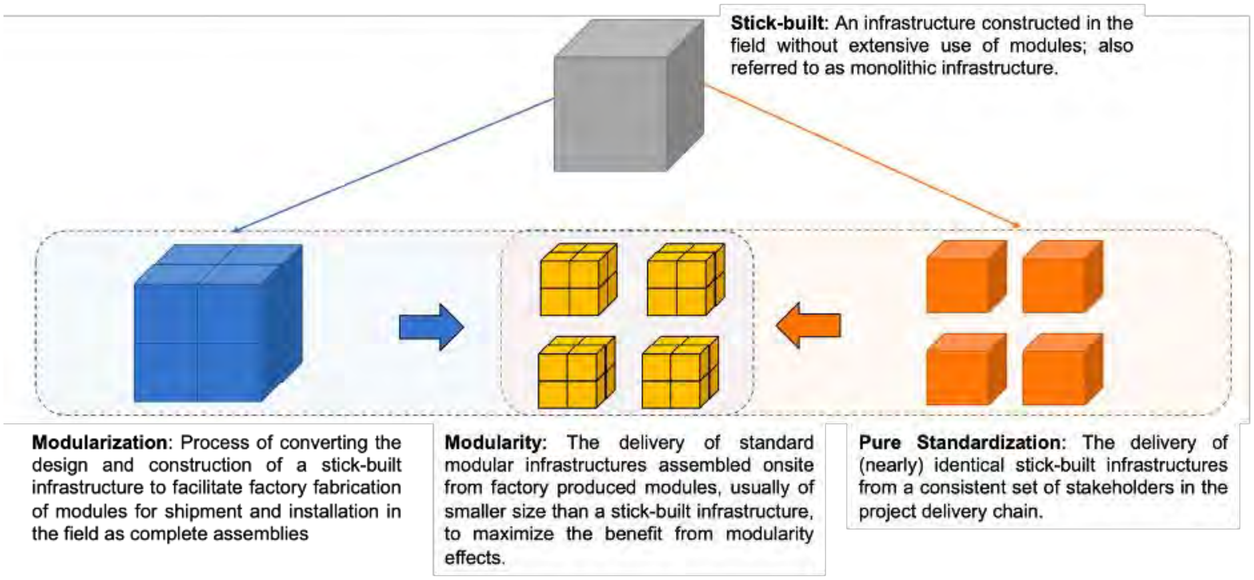
### Modularization

Modularization refers to converting the design into an assembly of smaller components that can be fabricated in a factory and assembled on site (Figure 13). Recent cost and schedule overruns in nuclear construction projects (for example in VC Summer and Vogtle), have driven the nuclear industry to move away from large, stick-built nuclear power plants and towards smaller and more modular reactors that are expected to minimize onsite labor and take advantage of factory manufacturing. This direction is further justified considering that the efficiency of the construction sector in the United States has fallen in the last few decades, whereas the efficiency of the manufacturing sector has gone up [56]. A plant of the same size and technology will likely have a smaller NOAK overnight capital cost when the design is modular, and the modules are factory fabricated. Modularization is, therefore, a primary cost reduction strategy of most reactor vendors that are currently in the process of developing their designs. It can be also implemented in various parts of the nuclear power plant.

NuScale, for example, has developed a reactor module that includes most of the NSSS components of a PWR. The NuScale VOYGR plant with a capacity of 984 MWe, has 12 such modules, which will be manufactured in a factory and installed on the site. However, historically, larger reactors have been predominantly stick-built and assembled on site. Another candidate for modularity in a nuclear power plant is the containment building—traditionally, these buildings are built by pouring concrete on site. However, modular concrete technologies such as precast concrete (which has been used in the non-nuclear industry for decades) or Steel Bricks$^{TM}$ [57] that are being deployed in the BWRX-300 plant, can lead to significant cost reduction for the same reactor size and technology type.

### Standardization:

Mignacca and Locatelli (2021) [58] define standardization as using "nearly identical stick-built infrastructures from a consistent set of stakeholders in the project delivery chain" (Figure 13). While standardization of nuclear power plants across the industry has brought success in a lot of places, this has eluded the nuclear industry of the United States thus far [59]. While it is unrealistic to standardize all plants across the United States, standardization can be accompanied with modularization. To enable efficient, mass factory fabrication, the modules need to be first standardized. Additionally, standardization can result in ease of licensing, ease of construction, quality control, and better learning, all of which contribute to lower NOAK costs.



**Stick-built**: An infrastructure constructed in the field without extensive use of modules; also referred to as monolithic infrastructure.

**Modularization**: Process of converting the design and construction of a stick-built infrastructure to facilitate factory fabrication of modules for shipment and installation in the field as complete assemblies

**Modularity:** The delivery of standard modular infrastructures assembled onsite from factory produced modules, usually of smaller size than a stick-built infrastructure, to maximize the benefit from modularity effects.

**Pure Standardization:** The delivery of (nearly) identical stick-built infrastructures from a consistent set of stakeholders in the project delivery chain.

Figure 13: An illustration of the relationship between modularization and standardization, and the difference between modular and stick-built infrastructure [58].

One approach for increasing standardization in a plant is seismic isolation [60]. Seismic isolation is an earthquake protection technology that involves using seismic protective devices under the plant (or a component of the plant) to essentially shield it from incoming earthquakes. Seismic isolation promotes plant standardization by enabling the use of the same design (with different seismic isolators) at different sites with differing earthquake hazards.

For example, a certified plant designed for the seismic hazard in New York may also be sited in Alaska (where the earthquake hazard is much larger) without any design changes, but with seismic isolators that are designed to protect the plant from the Alaskan seismic hazard. This can potentially reduce the re-design costs, seismic strengthening and re-qualification costs, and re-certification costs that could have been incurred at the Alaskan site. A few advanced reactor vendors are currently considering seismic isolation, including Kairos Power, whose 35 MWth Hermes test reactor will be seismically isolated, and Advanced Reactor Concepts, LLC, who are working on a 100 MWe seismically isolated SFR.

Another approach to increasing standardization is through the "open architecture" concept, which strives for standardization of plant components across different reactor technologies and developers. Implementation of this concept would require reactor developers to share and "open" their designs across the industry so that cross compatibility of components would be improved. Using similar components in various plant designs would have various benefits including simplifying the supply chain, transferring learning across different reactor technologies, increasing factory fabrication, simplifying construction, etc.

### Improved Plant Layout

Cost reductions can also be achieved through innovative design decisions in the plant layout. For example, the cost of construction inside a plant boundary can be several times larger (anecdotally up to five times larger) than the construction outside a plant boundary, due to additional regulations involved in nuclear construction. To minimize the amount of construction involved inside the plant boundary, TerraPower and GE Hitachi, in their Natrium (345 MWe SFR) design, separate the plant into a nuclear island that contains all nuclear safety-related (SR) and non-safety-related with special treatment (NSRST) components, and an energy island that contains thermal energy storage and electricity production components [61]. This enables the separation of construction activities in the nuclear island and energy island (including contracting with separate EPCs), which is potentially much cheaper than a similarly sized SFR constructed with the traditional approach of including all components inside the plant boundary.

Another example of cost reduction through an innovative plant layout is the Boston Atomics' HC-HTGR. In a traditional HTGR (such as in NGNP), the reactor vessel and steam generator are constructed vertically inside the reactor building. Although they have a high degree of passive safety, HTGRs are criticized for their low power density and large building sizes that drive construction costs[a]. The HC-HTGR remedies these issues by mounting the reactor vessel and steam generator horizontally. By doing so, they estimate a total overnight capital cost reduction of 20% including a 42% reduction in civil structure costs, and 38% reduction in indirect costs [22].

## 3.4 Areas of Improvement

### Additional Postprocessing of Data

Future efforts could attempt to address many of the limitations highlighted previously. Some suggested improvements are summarized below:

1. Weighing of estimates: since weighing studies is an inherently subjective task, a panel could be conferred to attribute different weights depending on pre-defined metrics (e.g., age of estimates, type of analysis, observed vs. projected costs). This could then be used to provide a stronger basis for the data aggregation conducted in the study.
2. Re-baselining of estimates: since not all estimates included the same cost contributors. These could be inferred from typical breakdowns for reactor types and used as multiplier for each dataset to account for the missing data (e.g., owners' costs) or subtract localized costs (e.g., financing costs).
3. More robust escalation: because the impact of escalating costs was found to be a substantial driver in estimates, a more detailed approach may be warranted. Comparative evaluation may

---

[a] For example, Stewart et al. (2021) estimate that the reactor building power density of the 220 MWe HTR-PM (twin pack of 110 MWe reactors in one building) recently built by the China National Nuclear Corporation is six times smaller (2 kWe/m$^3$) than of the 1117 MWe Westinghouse AP1000 plant (12 kWe/m$^3$). The reactor pressure vessel power density of the HTR-PM reactor us 150 kWe/ton compared to 315 kWe/ton for APR1000.

provide additional confidence in the best approach for cost escalation or alternatively be leveraged as a basis for a range.

4. Identifying overlap in the data: several of the cost estimates build or rely on each other. Namely the Energy Economic Data Base (EEDB) program from the 1980s [62]. Identifying these dependencies may lead to lower weights assigned to estimates that rely heavily on previous datasets or their removal from the dataset entirely to avoid ‘double-counting’. Additionally, these cost estimates may need to be ‘de-escalated’ and then ‘re-escalated’ following a consistent methodology.
5. A statistical (or econometric) model could be developed to mathematically infer some of the conclusions from the evaluation, namely that plant size and reactor type appear to have limited impact on costs. This would support the visually-inferred conclusions from whisker plots in the report.

In general, generating more robust cost estimates for advanced reactors in a systematic, standardized fashion would be an ideal method to tackling the challenge of projecting advanced reactor deployment costs. Modern estimates would be more representative of likely cost ranges for these estimates. This would be preferable to relying on decade-old references and mathematically inflating the costs to current levels—as was performed in this study. Detailed bottom-up estimates following the code of accounts structure can also be critical in identifying nuances between different types of reactors (which is another limitation of the current study).

## Uncertainty Analysis

During the analysis, large variances in cost estimates from different literatures were observed. These differences introduce uncertainties to the economic estimates and the resulting recommendations. To characterize such uncertainties and better understand the major contributors, a systematic uncertainty quantification (UQ) would be needed. The scope of this would need to include a review of assumptions, inputs, and data sources on the final estimations in each reference. UQ can also help economic analysts and decision-makers understand the robustness of economic models and corresponding forecasts. There are several potential methods for economic model UQ. The sensitivity analysis varies the input parameters of the economic model one at a time or in combination and observing the resulting changes in the model's output. This approach can help identify the most important parameters and sources of uncertainty, and directly inform the development of robust economic models and decision-making that are resilient to different scenarios. The Monte Carlo simulation starts from building probabilistic distributions for different sources of uncertainty. Next, a large number of random samples for each input are drawn, and the economic model is run multiple times with each sample to generate a distribution of output values. This approach can provide a comprehensive view of the uncertainty associated with the model's outputs. For efficiency, samples are only drawn from important inputs based on the sensitivity analysis results. In addition to the probabilistic approach, interval analysis starts from representing the uncertainty of input parameters as intervals or ranges of values rather than a well-characterized distribution, which assumes precise probabilities for each possible value. The uncertainty of each input parameter can be better quantified through the economic model. Interval analysis can also provide a more conservative estimate of uncertainty, by accounting for the full range of possible values for each parameter. Compared to the Monte Carlo approach, interval analysis can be useful for situations where the available data is uncertain or incomplete, or where there is a high degree of variability in the data.

RAVEN (Risk Analysis and Virtual ENvironments) is an open-source software tool developed by the Idaho National Laboratory for UQ and risk analysis [63]. RAVEN contains various libraries for both the sensitivity analysis and Monte Carlo UQ of economic models, providing a comprehensive and flexible platform for performing probabilistic and non-probabilistic analyses of complex systems. For probabilistic or non-probabilistic approaches, the UQ for an economic model should first dive into each reference and identify model assumptions, model inputs, and parameters for the final estimates. The objective is to find major sources of uncertainty and specify the probability distributions or intervals for the model parameters of the economic model. RAVEN provides a wide range of distribution types, including normal, lognormal, uniform, and beta distributions, as well as the ability to define custom distributions.

Next, the uncertainty propagation is performed by generating a large number of random samples of the input parameters from their specified probability distributions or ranges and running the economic model multiple times to generate a distribution of output values. RAVEN can also be used to perform sensitivity analysis of the economic model, which involves varying the input parameters one at a time or in combination and observing the resulting changes in the model's output. This can help identify the most important parameters and sources of uncertainty in the model. Finally, the results of the UQ analysis can be interpreted and visualized using RAVEN's built-in tools, including histograms, scatterplots, and probability density functions. This can help provide insights into the uncertainty and variability in the economic model and inform decision-making.

# 4. CONCLUSION

A detailed review of over 30 references in the advanced reactor cost estimation was performed in this report. The study compiled cost data in the literature and scaled costs to a common base year. While the data contained some inconsistencies, the estimates were still useful in elucidating trends in reactor costs. Identified cost ranges were evaluated from the dataset.

A key finding from this report is that there does not exist sufficient consensus in the cost estimation literature to adequately distinguish between reactor types. In other words, the report could not identify clear cost variations between water, sodium, gas, or salt cooled reactors. Similarly, estimates for large reactors and SMRs overlapped substantially. As such, a single value is recommended for large or small modular reactors, irrespective of their coolant type. The only exception is for microreactors. Here, a separate estimate is recommended. However, this is based on only two datasets and should be revisited as the technology matures and more cost evaluations for this class of reactors is conducted.

The OCC and OPEX identified values were provided within a low/medium/high range. This would correspond to underlying assumptions regarding a given use case (e.g., optimistic construction timeline). The estimates are for a generic BOAK reactor deployment (between a first and Nth of a kind). However, several cost adjustments were also provided in order to further refine the evaluation. This included FOAK premium multipliers, learning rates, and multi-unit correction factors (savings due to the pooling of infrastructure and resources between plants).

Lastly, a detailed breakdown of the contribution of subcomponents to different reactors was provided in percentage values. This allows a user to identify (and subtract as needed) the contribution of, for example, turbine costs, to the total overnight costs for a given system. These breakdowns were obtained from detailed bottom-up estimates for reference reactor types (water, sodium, gas, and salt-based). The intent is to provide an end-user with additional flexibility to refine nuclear cost estimates.

# 5. REFERENCES

[1] AspenTech, "Aspen Process Economic Analyzer," [Online]. Available: https://www.aspentech.com/en/products/pages/aspen-process-economic-analyzer. [Accessed 12 October 2022].

[2] J. Buongiorno, J. Parsons, D. Petti and J. Parsons, "The future of nuclear energy in a carbon-constrained world," MIT, Cambridge, MA, 2019.

[3] J. Hansen, W. Jenson, A. M. Wrobel, N. Stauff, K. Biegel, T. K. Kim, R. Belles and F. Omitaomu, "Investigating Benefits and Challenges of Converting Retiring Coal Plants into Nuclear Plants," Idaho National Laboratory, INL/RPT-22-67964-Rev000 , Idaho Falls, 2022.

[4] X-Energy, "X-Energy Investor Presentation," X-Energy, LLC, 2023. [Online]. Available: https://x-energy.com/investors. [Accessed 27 Feburary 2023].

[5] S. Short and B. Schmitt, "Deployability of Small Modular Nuclear Reactors for Alberta Applications—Phase II," Pacific Northwest National Laboratory, Richland, WA, 2018.

[6] W. Stewart and K. Shirvan, "Capital cost estimation for advanced nuclear power plants," *Renewable and Sustainable Energy Reviews,* p. 111880, 2021.

[7] World Nuclear News, "NuScale announces SMR power uprate," World Nuclear News, 11 November 2020. [Online]. Available: https://www.world-nuclear-news.org/Articles/NuScale-announces-SMR-power-uprate#:%7E:text=The%20increase%20in%20generating%20capacity,about%20USD2850%2C%20the%20company%20said. [Accessed 1 Feburary 2023].

[8] D. Schlissel, "Eye-popping new cost estimates released for NuScale small modular reactor," Institute for Energy Economics and Financial Analysis, 11 January 2023. [Online]. Available: https://ieefa.org/resources/eye-popping-new-cost-estimates-released-nuscale-small-modular-reactor#:~:text=NuScale%20and%20the%20Utah%20Associated,(SMR)%20have%20risen%20dramatically.&text=As%20recently%20as%20mid%2D2021,MWh%2C%20a%2053%25%20increase.. [Accessed 24 May 2023].

[9] A. Foss, H. Bryan and P. Jeremiah, "Cost Assessment of Small and Micro Nuclear Reactors for Oil Sands Applications (INL/LTD-21-01565)," Idaho National Laboratory, Idaho Falls, ID, 2021.

[10] M. Weimar, A. Zbib, D. Todd, J. Buongiorno and K. Shirvan, "Techno-economic Assessment for Generation III+ Small Modular Reactor Deployments in the Pacific Northwest," Pacific Northwest National Laboratory, Richland, Washington, 2021.

[11] J. Surina, *NuScale Power Plant Economics (Presentation),* NuFab, Northwestern University: NuScale Power LLC, 2016.

[12] J. Surina and M. McGough, *The NuScale Value Proposition (Presentation),* NuScale Power LLC, 2015.

[13] Energy Strategies, "Analyzing the Cost of Small Modular Reactors and Alternative Power Portfolios," Energy Strategies, Salt Lake City, UT, 2019.

[14] S. Kirshenberg, H. Jackler, J. Eun, B. Oakley and W. Goldenberg, "Small Modular Reactors, Adding to Resilience at Federal Facilities," Allegheny Science & Technology Corporation, Bridgeport, WV, 2017.

[15] U.S. Energy Information Administration, "Capital Cost and Performance Characteristic Estimates for Utility Scale Electric Power Generating Technologies," U.S. Energy Information Administration, 2020.

[16] SMR Start, "The Economics of Small Modular Reactors," SMR Start, 2021.

[17] W. Stewart, K. Shirvan, E. Velez and R. Wiser, "Pathways to Cost-effective Advanced Nuclear Technology," in *Applied Energy Symposium MIT A+B*, Cambridge, MA, 2020.

[18] National Renewable Energy Laboratory, "Electricity Annual Technology Baseline (ATB) Data Download," 19 Feburary 2023. [Online]. Available: https://atb.nrel.gov/electricity/2022/data.

[19] LAZARD, "Lazard's Levelized Cost of Energy Analysis - Version 16.0," LAZARD, April 2023. [Online]. Available: https://www.lazard.com/research-insights/2023-levelized-cost-of-energyplus/. [Accessed 18 April 2023].

[20] D. Holcomb, F. Peretz and A. Qualls, "Advanced high temperature reactor systems and economic analysis," Argonne National Laboratory, 2011.

[21] A. Gandrik, B. Wallace, M. Patterson and P. Mills, "Assessment of high temperature gas cooled reactor capital and operating costs (TEV-1196)," Idaho National Laboratory, Idaho Falls, ID, 2012.

[22] W. Stewart, E. Velez, R. Wiser and K. Shirvan, "Economic solution for low carbon process heat: A horizontal, compact high temperature gas reactor," *Applied Energy,* p. 117650, 2021.

[23] Department of Energy, "Modular High Temparature Gas-Cooled Reactor Commercialization and Generation Cost Estimates (https://doi.org/10.2172/10198837)," Department of Energy, 1993.

[24] CleanTech Catalyst Ltd; Lucid Strategy, Inc., "The ETI Nuclear Cost Drivers Project: Summary Report," Energy Technologies institute, 2018.

[25] V. Kuznetsov and A. Lokhov, "Current status, technical feasibility and economics of small nuclear reactors," Nuclear energy agency of the Organisation of economic cooperation and development, Paris, France, 2011.

[26] F. Ganda, "Economic Evaluation of Promising Options (No. FCRD-FCO-2015-000013)," Argonne National Laboratory, Argonne, IL, 2015.

[27] F. Ganda, T. Taiwo and T. Kim, "Report on the Update of Fuel Cycle Cost Algorithms (No. NTRD-FCO-2018-000439)," Argonne National Laboratory, Argonne, IL, 2018.

[28] D. Shropshire, "Advanced fuel cycle economic tools algorithms, and methodologies (No. INL/EXT-09-15483)," Idaho National Laboratory, Idaho Falls, ID, 2009.

[29] C. E. Boardman, "Economic assessment of S-PRISM including development and generating costs," ICONE, 2000.

[30] E. A. Hoffman, R. N. Hill and P. J. Finck, "Estimated Cost for Low Conversion Ratio Burners," Argonne National Laboratory, Lemont, IL, 2004.

[31] J. Engel, H. Bauman, J. Dearing, W. Grimes, H. McCoy and W. Rhoades, "Conceptual design characteristics of a denatured molten-salt reactor with once-through fueling (No. ORNL/TM-7207)," Oak Ridge National Laboratory, Knoxville, TN, 1980.

[32] M. Nichol and H. Desai, "Cost competitiveness of micro-reactors for remote markets," Nuclear Energy Institute (NEI), Washington, DC, 2019.

[33] A. Abou-Jaoude, Y. Arafat, A. Foss and B. Dixon, "An Economics-by-Design Approach Applied to a Heat Pipe Microreactor Concept (No. INL/EXT-21-63067-Rev000)," Idaho National Lab.(INL), Idaho Falls, ID, 2021.

[34] Energy Innovation Reform Project, "What will advanced nuclear power plants cost? A Standardized Cost Analysis of Advanced Nuclear Technologies in Commercial Development," Energy Innovation Reform Project, 2017.

[35] Breakthrough Institute, "Advancing Nuclear Energy: Evaluating Deployment, Investment, and Impact in America's Clean Energy Future," Breakthrough Institute, 2022.

[36] J. Lovering, A. Yip and T. Nordhau, "Historical construction costs of global nuclear power reactors," *Energy Policy,* vol. 91, pp. 371-382, 2016.

[37] B. Dixon, F. Ganda, K. Williams, E. Hoffman and J. K. Hansen, "Advanced Fuel Cycle Cost Basis–2017 Edition," Idaho National Laboratory, Idaho Falls, ID, 2017.

[38] Federal Reserve Bank of St. Louis, "Producer Price Index by Commodity: Construction (Partial): New Industrial Building Construction," Federal Reserve Bank of St. Louis, 11 May 2023. [Online]. Available: https://fred.stlouisfed.org/series/WPU801104#0. [Accessed 24 May 2023].

[39] ANS Nuclear Cafe, "Vogtle project update: Cost likely to top $30 billion," American Nuclear Society, 9 May 2022. [Online]. Available: https://www.ans.org/news/article-3949/vogtle-project-update-cost-likely-to-top-30-billion/. [Accessed 1 May 2023].

[40] National Association of Regulatory Utility Commissioners (NARUC), "COST OF CAPITAL AND CAPITAL MARKETS A PRIMER FOR UTILITY REGULATORS," United States Agency for International Development (USAID), 2019.

[41] U.S. Nuclear Regulatory Commission, "Status of Initial License Renewal Applications and Industry Initiatives," [Online]. Available: https://www.nrc.gov/reactors/operating/licensing/renewal/applications.html. [Accessed April 2023].

[42] Energy Information Agency, "Electric Power Monthly," [Online]. Available: https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_b. [Accessed April 2023].

[43] J. Greenwald, C. Mokoena, M. Chupka and M. Luke, "Modeling Advanced Nuclear Energy Technologies," Nuclear Innovation Alliance (NIA), 2023.

[44] X-energy, "X-energy ARDP," [Online]. Available: https://x-energy.com/ardp. [Accessed 6 October 2023].

[45] S&P Global, "Bill Gates-backed TerraPower tabs Wyoming site for $4B 'next wave' nuclear plant," 16 November 2021. [Online]. Available: https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/bill-gates-backed-terrapower-tabs-wyoming-site-for-4b-next-wave-nuclear-plant-67676344.

[46] U.S. Department of Energy, "Phase VIII update (1986) report for the Energy Economic Data Base Program EEDB-VIII (No. DOE/NE--0079)," U.S. Department of Energy, 1986.

[47] A. Abou-Jaoude, C. Bolisetti and A. Foss, "Expansion of Cost Algorithm and Technoeconomic Assessment Capabilities," Idaho National Laboratory, Idaho Falls, INL/RPT-22-67852, 2022.

[48] E. Ingersoll, K. Gogan, J. Herter and A. Foss, "Cost & Performance Requirements for Flexible Advanced Nuclear Plants in Future US Power Markets," LucidCatalyst LLC, Cambridge, MA , 2020.

[49] Generation IV International Forum (GIF), "Cost Estimating Guidelines for Generation IV Nuclear Energy Systems," Economic Modeling Working Group. https://www.gen-4.org/gif/jcms/c_40408/cost-estimating-guidelines-for-generation-iv-nuclear-energy-systems, 2007.

[50] P. Sabharwall, S. Bragg-Sitton, L. Boldon and S. Blumsack, "Nuclear renewable energy integration: an economic case study," *The Electricity Journal,* vol. 28, no. 8, pp. 85-95, 2015.

[51] T. Harrison, "Development of the Mathematics of Learning Curve Models for Evaluating Small Modular Reactor Economics (No. ORNL/TM-2014/28)," Oak Ridge National Laboratory, Oak Ridge, TN, 2014.

[52] K. Shirvan and J. Hardwick, "Overnight capital cost of the next AP1000 (MIT-ANP-TR-193)," Center for Advanced Nuclear Energy Systems (CANES), Boston, MA, 2022.

[53] T. P. Wright, "Factors Affecting the Cost of Airplanes," *Journal of the Aeronautical Sciences,* vol. 3, no. 4, pp. 122-128, 1936.

[54] G. Mislick and D. Nussbaum, Cost Estimation: Methods and Tools, New York: Wiley, 2015.

[55] NEI, "Nuclear Costs in Context," Nuclear Energy Institute, 2022.

[56] F. Barbosa, J. Woetzel, J. Mischke, M. Ribeirinho, M. Sridhar, M. Parsons, N. Bertram and S. Brown, "Reinventing construction: a route to higher productivity," McKinsey Global Institute, 2021.

[57] A. Larson, "Innovative 'Steel Bricks' Design Expected to Reduce Time, Cost of SMR Construction," POWER, 22 April 2021. [Online]. Available: https://www.powermag.com/innovative-steel-bricks-design-expected-to-reduce-time-cost-of-smr-construction/. [Accessed 1 May 2023].

[58] B. Mignacca and G. Locatelli, "Modular circular economy in energy infrastructure projects: Enabling factors and barriers," *Journal of Management in Engineering,* vol. 37, no. 5, p. 04021053, 2021.

[59] P. David and G. Rothwell, "Measuring standardization: An application to the American and French nuclear power industries," *European Journal of Political Economy,* vol. 12, no. 2, pp. 291-308, 1996.

[60] S. Parsi, K. Lal, B. Kosbab, E. Ingersoll, K. Shirvan and A. Whittaker, "Seismic isolation: A pathway to standardized advanced nuclear reactors," *uclear Engineering And Design,* vol. 387, p. 111445, 2022.

[61] Terra Power, "Energy Island Decoupling Strategy (NATD-LIC-STDY-0001) White Paper," U.S. Nuclear Regulatory Commission, Bellevue, WA, 2022.

[62] United Engineers & Constructors Inc., "technical reference book for the energy economic data base program (EEDB)," U.S. Department of Energy, Washington, D.C., 1986.

[63] C. Rabiti, A. Alfonsi, J. Joshua Cogliati, D. Mandelli, R. Kinoshita, S. Sonat Sen, C. Wang, P. Talbot and D. Maljovec, "RAVEN User Manual," Idaho National Laboratory, INL/EXT-15-34123 Revision 7, Idaho Falls, 2019.

[64] Board of Governors of the Federal Reserve System (US), "Industrial Production: Utilities: Nuclear Electric Power Generation (NAICS = 221113) [IPN221113S]," FRED, Federal Reserve Bank of St. Louis, [Online]. Available: https://fred.stlouisfed.org/series/IPN221113S. [Accessed 19 January 2023].

[65] L. Demick and D. Vandel, "Next generation nuclear plant pre-conceptual design report (No. INL/EXT-07-12967)," Idaho National Laboratory, Idahl Falls, ID, 2007.

[66] C. Boardman, "Economic assessment of S-PRISM including development and generating costs," in *ICONE*, 2001.

# APPENDIX A

# Processing of the Cost Estimate Dataset

## A.1 Overview of Some Inconsistencies in Cost Dataset

As disclosed in Section 2.1, the various cost estimate references contained inconsistencies among themselves. Namely as it relates to financing costs, owners' costs, and pre-construction costs. To showcase this issue, Table 17 provides an overview of which reference accounts for financing costs. Despite these limitations the analysis did not attempt to re-baseline estimates in the literature.

Table 17. Overview of which dataset includes financing costs for nuclear reactors.

| | | Reactor Concept | Units | Power | Specific costs | Includes Financing Costs? |
|---|---|---|---|---|---|---|
| PWR | [5] | NuScale iPWR | 12 | 1920MWth/570MWe | 5,100$\$_{2015}$/kWe | No |
| | [6] | NuScale iPWR | 12 | 685MWe | 3,856$\$_{2018}$/kWe | No |
| | [7] | NuScale VOYGR | 12 | 924MWe | 2,850$\$_{2018}$/kWe | No |
| | [8] | NuScale/UAMPS | 6 | 462MWe | 20,139$\$_{2022}$/kWe | Yes |
| | [9] | SMART iPWR | — | — | 5,600$\$_{2014}$/kWe | No |
| | [10] | NuScale SMR | — | 1920-2400MWth/600-720MWe | — | Yes |
| | [13] | NuScale | — | 600MWe | — | Unclear |
| | [14] | SMR | — | 570MWe | — | Uncertain |
| | [15] | SMR | 12 | 600MWe | 6,191$\$_{2019}$/KWe | No |
| | [16] | SMR | 4 | 600MWe | 3,800$\$_{2020}$/MW-hr | No |
| | [16] | SMR | 4 | 600MWe | 2,000$\$_{2020}$/MW-hr | No |
| | [10] | GEH BWRX-300 | — | 870MWth/300MWe | — | No |
| | [17] | PWR-12 | 1 | 3417MWth/1144MWe | 6,345$\$_{2017}$/kWe | Yes |
| | [17] | PWR-12 | 1 | 3417MWth/1144MWe | 3,650$\$_{2017}$/kWe | No |
| | [17] | AP1000 | 1 | 3417MWth/1144MWe | 6,671$\$_{2017}$/kWe | No |
| | [17] | AP1000 | 1 | 3415MWth/1100MWe | 3,838$\$_{2017}$/kWe | No |
| | [18] | AP1000 | 1 | 3415MWth/1100MWe | 7,349$\$_{2022}$/kWe | No |
| | [2] | PWR | 1 | 3415MWth/1100MWe | 6,154$\$_{2018}$/kWe | No |
| | [2] | PWR | 1 | 3415MWth/1100MWe | 6,986$\$_{2014}$/kWe | No |
| | [15] | PWR | 2 | 2156 MWe | 6,041$\$_{2019}$/KWe | No |
| | [10] | PWR | 2 | 2256MWe | 6,317$\$_{2019}$/KWe | No |
| | [19] | PWR | — | — | — | Yes |
| | [20] | PWR12BE | 1 | 3417MWth/1144MWe | 3,054$\$_{2011}$/kWe | Yes |
| | [20] | PWR12ME | 1 | 3417MWth/1144Mwe | 5,305$\$_{2011}$/kWe | No |
| | [20] | PWR Improved | 1 | 3417MWth/1144Mwe | 2,534$\$_{2011}$/kWe | No |
| HTGR | [17] | NGNP | 1 | 275MW | 9,900$\$_{2017}$/kWe | No |
| | [9] | HTGR | — | — | 6,600$\$_{2015}$/kWe | No |
| | [17] | MIGHTR | 1 | 350MWth/154MWe | 7,346$\$_{2017}$/kWe | No |
| | [21] | NGNP | 1 | 350MWth/156MWe | 20,994$\$_{2009}$/kWe | No |
| | [21] | NGNP | 1 | 600MWth/267MWe | 14,479$\$_{2009}$/kWe | No |
| | [21] | NGNP | 1 | 350MWth/154MWe | 7,324$\$_{2009}$/kWe | No |

| | | | | | | |
|---|---|---|---|---|---|---|
| | [21] | NGNP | 1 | 600MWth/267MWe | 5,841$\$_{2009}$/kWe | No |
| | [2] | NGNP | 4 | 2400MWth/1000MWe | 5,246$\$_{2009}$/kWe | No |
| | [17] | NGNP | 4 | 1100 MW | 4,814$\$_{2017}$/kWe | No |
| | [21] | NGNP | 4 | 1400MWth/624MWe | 5,720$\$_{2009}$/kWe | No |
| | [17] | MIGHTR | 4 | 1400MWth/616MWe | 3,585$\$_{2017}$/kWe | No |
| | [21] | NGNP | 4 | 2400MWth/1068MWe | 4,663$\$_{2009}$/kWe | No |
| | [22] | NGNP | 4 | 2400MWth/1068MWe | 5,600$\$_{2018}$/kWe | No |
| | [22] | HC-HTGR | 4 | 920MWe | 4,550$\$_{2018}$/kWe | No |
| | [22] | HC-HTGR | 4 | 920MWe | 3,000$\$_{2018}$/kWe | No |
| | [23] | MHTGR-SC | 4 | 1800MWth/693MWe | 3,153$\$_{1992}$/kWe | No |
| | [23] | MHTGR-SC | 4 | 1800MWth/693MWe | 2,347$\$_{1992}$/kWe | No |
| | [23] | MHTGR-GT/IC | 4 | 1800MWth/806MWe | 3,290$\$_{1992}$/kWe | No |
| | [23] | MHTGR-GT/IC | 4 | 1800MWth/806MWe | 2,458$\$_{1992}$/kWe | No |
| | [23] | MHTGR-GT/DC | 4 | 1800MWth/869MWe | 2,656$\$_{1992}$/kWe | No |
| | [23] | MHTGR-GT/DC | 4 | 1800MWth/869MWe | 1,908$\$_{1992}$/kWe | No |
| | [24] | HTGR | — | 1124MWe | 5,469$\$_{2017}$/kWe | No |
| **SFR** | [2] | SFR | 4 | 3360MWth/1100MWe | 5,632$\$_{2013}$/kWe | No |
| | [25] | 4S Sodium | 1 | 30MWth | — | No |
| | [26] | LSPB | 1 | 1100MWe | 4,734$\$_{2013}$/kWe | No |
| | [27] | ABR1000 | 1 | 380MWe | 5,612$\$_{2017}$/kWe | No |
| | [28] | S-PRISM | 4 | 1520MWe | 2,664$\$_{2005}$/kWe | Yes |
| | [28] | S-PRISM | 4 | 1520MWe | 3,046$\$_{2005}$/kWe | Yes |
| | [29] | S-PRISM | 2 | 1651MWe | 1,334$\$_{1996}$/kW | Yes |
| | [28] | S-PRISM Mod B | 6 | 1866MWe | 2,073$\$_{2005}$/kWe | Yes |
| | [28] | S-PRISM Mod B | 6 | 1866MWe | 2,371$\$_{2005}$/kWe | Yes |
| | [30] | S-PRISM Mod B | 6 | 1866MWe | 1,554$\$_{2004}$/kWe | No |
| | [24] | LSPB | — | 1311Mwe | 4,240$\$_{2017}$/kWe | No |
| **MSR** | [2] | AHTR | 1 | 3000MWth/1350MWe | 5,217$\$_{2011}$/kWe | No |
| | [2] | MSR | 1 | 2275MWth/1000MWe | 6,113$\$_{2011}$/kWe | No |
| | [2] | FHR | 12 | 2904MWth/1330MWe | 5,423$\$_{2015}$/kWe | No |
| | [31] | DMSR | 1 | 1000MW | 6,53$\$_{1978}$/kWe | No |
| | [20] | AHTR | 1 | 3400MWth/1530MWe | 3,384$\$_{2011}$/kWe | No |
| | [24] | MSR | — | 190-1000MWe | 3,664$\$_{2017}$/kWe | No |
| **Microreactor** | [32] | Reference micro-reactor | 1 | 10MWth/5MWe | 10,000$\$_{2019}$/kWe | No |
| | [32] | Reference micro-reactor | 1 | 10MWth/5MWe | 15,000$\$_{2019}$/kWe | No |
| | [32] | Reference micro-reactor | 1 | 10MWth/5MWe | 20,000$\$_{2019}$/kWe | No |
| | [32] | Reference micro-reactor | 1 | 10MWth/5MWe | 3,996$\$_{2019}$/kWe | No |
| | [32] | Reference micro-reactor | 1 | 10MWth/5MWe | 8,276$\$_{2019}$/kWe | No |
| | [32] | Reference micro-reactor | 1 | 10MWth/5MWe | 14,973$\$_{2019}$/kWe | No |
| | [33] | Design A | 1 | 5MWth/1.8MWe | 65,445$\$_{2017}$/kWe | Yes |
| | [33] | Design A’ | 1 | 8MWth/2.9MWe | 19,241$\$_{2017}$/kWe | Yes |
| | [33] | Design A’ | 1 | 8MWth/2.9MWe | 6,575$\$_{2017}$/kWe | Yes |

## A.2. Adjusted Cost Estimates Using Escalation Methdodology

The values in Note that cost estimates from the Advanced Reactor Demonstration Program (ARDP) were not included because public statements regarding overall costs do not include breakdowns of reactor costs against other expenses. Reference [4] highlights how one of the ARDP awardees intends to use the total budget for completing the design, obtaining license approval, and construction of a fuel fabrication facility, in addition to the reactor demonstration costs.

Table 2 are re-baselined to 2019 USD in the table below using the methodology outlined in Section 2.3. These values were subsequently used in the study to derive trends and identify ranges in cost estimates.

Table 18. Overview of escalated costs (2019$) for each reference used in the study.

| | | | **Original Year Value** | | | **Escalated Value** | | |
|---|---|---|---|---|---|---|---|---|
| | | **Reactor Concept** | **Specific costs** | **LCOE** | **OPEX** | **Specific costs** | **LCOE** | **OPEX** |
| **PWR** | [5] | NuScale iPWR | 5100$\$_{2015}$/kW | 114$\$_{2015}$/MW-hr | — | 5941$\$_{2019}$/kW | 133$\$_{2019}$/MW-hr | — |
| | [6] | NuScale iPWR | 3856$\$_{2018}$/kW | — | — | 4085$\$_{2019}$/kW | — | — |
| | [7] | NuScale iPWR | 2850$\$_{2018}$/kW | — | — | 3019$\$_{2019}$/kW | — | — |
| | [9] | SMART iPWR | 5600$\$_{2015}$/kWe | 105$\$_{2015}$/MW-hr | 25$\$_{2015}$/MW-hr | 6400$\$_{2019}$/kWe | 123$\$_{2019}$/MW-hr | 30$\$_{2019}$/ MW-hr |
| | [10] | NuScale SMR | — | 51-54$\$_{2019}$/MW-hr<br>112$\$_{2016}$/MW-hr [11]<br>101$\$_{2016}$/MW-hr [12] | — | — | 51-54$\$_{2019}$/MW-hr<br>127$\$_{2019}$/MW-hr [11]<br>115$\$_{2019}$/MW-hr [12] | — |
| | [13] | NuScale | — | 65$\$_{2015}$/MW-hr | — | — | 75$\$_{2019}$/MW-hr | — |
| | [14] | SMR | — | 80$/MW-hr | — | — | 89$\$_{2019}$/MW-hr | — |
| | [15] | SMR | 6191$\$_{2019}$/KWe | — | — | 6191$\$_{2019}$/KWe | — | — |
| | [16] | SMR | 3800$\$_{2020}$/MW-hr | 95$\$_{2020}$/MW-hr | 22$\$_{2020}$/MW-hr | 3690$\$_{2019}$/MW-hr | 93$\$_{2019}$/MW-hr | 22$\$_{2019}$/ MW-hr |
| | [16] | SMR | 2000$\$_{2020}$/MW-hr | 44$\$_{2020}$/MW-hr | 15$\$_{2020}$/MW-hr | 1942$\$_{2019}$/MW-hr | 43$\$_{2019}$/MW-hr | 15$\$_{2019}$/ MW-hr |
| | [10] | GEH BWRX-300 | — | 44–51$\$_{2019}$/MW-hr | — | — | 44–51$\$_{2019}$/MW-hr | — |
| | [17] | PWR-12 | 6345$\$_{2017}$/kWe | — | — | 7392$\$_{2019}$/kWe | — | — |
| | [17] | PWR-12 | 3650$\$_{2017}$/kWe | — | — | 4253$\$_{2019}$/kWe | — | — |
| | [17] | AP1000 | 6671$\$_{2017}$/kWe | — | — | 7402$\$_{2019}$/kWe | — | — |
| | [17] | AP1000 | 3838$\$_{2017}$/kWe | — | — | 4259$\$_{2019}$/kWe | — | — |
| | [18] | AP1000 | 7349$\$_{2022}$/kWe | 81$\$_{2022}$/MW-hr | — | 5546$\$_{2019}$/kWe | 62$\$_{2019}$/MW-hr | — |
| | [2] | PWR | 6154$\$_{2018}$/kWe | — | — | 6518$\$_{2019}$/kWe | — | — |
| | [2] | PWR | 6986$\$_{2014}$/kWe | — | — | 8138$\$_{2019}$/kWe | — | — |
| | [15] | PWR | 6041$\$_{2019}$/KWe | — | — | 6041$\$_{2019}$/KWe | — | — |
| | [10] | PWR | 6317$\$_{2019}$/KWe | 82$\$_{2019}$/ MW-hr | 25$\$_{2019}$/ MW-hr | 6317$\$_{2019}$/KWe | 82$\$_{2019}$/ MW-hr | 25$\$_{2019}$/ MW-hr |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | [19] | PWR | — | 141-221$\$_{2023}$/MW-hr | 19-21$\$_{2023}$/MW-hr | — | 107-167$\$_{2019}$/MW-hr | 15-16$\$_{2019}$/MW-hr |
| | [20] | PWR12BE | 3054$\$_{2011}$/kWe | — | — | 3762$\$_{2019}$/kWe | — | — |
| | [20] | PWR12ME | 5305$\$_{2011}$/kWe | — | — | 6535$\$_{2019}$/kWe | — | — |
| | [20] | PWR Improved | 2534$\$_{2011}$/kWe | — | — | 3122$\$_{2019}$/kWe | — | — |
| **HTGR** | [17] | NGNP | 9900$\$_{2017}$/kWe | — | — | 10984$\$_{2019}$/kWe | — | — |
| | [9] | HTGR | 6600$\$_{2015}$/kWe | 128$\$_{2015}$/MW-hr | 30$\$_{2015}$/MW-hr | 7543$\$_{2019}$/kWe | 147$\$_{2019}$/MW-hr | 35$\$_{2019}$/MW-hr |
| | [17] | MIGHTR | 7346$\$_{2017}$/kWe | — | — | 8151$\$_{2019}$/kWe | — | — |
| | [21] | NGNP | 20994$\$_{2009}$/kWe | — | — | 26554$\$_{2019}$/kWe | — | — |
| | [21] | NGNP | 14479$\$_{2009}$/kWe | — | — | 18314$\$_{2019}$/kWe | — | — |
| | [21] | NGNP | 7324$\$_{2009}$/kWe | — | — | 9264$\$_{2019}$/kWe | — | — |
| | [21] | NGNP | 5841$\$_{2009}$/kWe | — | — | 7389$\$_{2019}$/kWe | — | — |
| | [2] | NGNP | 5246$\$_{2009}$/kWe | 114$\$_{2009}$/MW-hr | — | 6636$\$_{2019}$/kWe | 145$\$_{2019}$/MW-hr | — |
| | [17] | NGNP | 4814$\$_{2017}$/kWe | — | — | 5342$\$_{2019}$/kWe | — | — |
| | [21] | NGNP | 5720$\$_{2009}$/kWe | — | — | 7236$\$_{2019}$/kWe | — | — |
| | [17] | MIGHTR | 3585$\$_{2017}$/kWe | — | — | 3978$\$_{2019}$/kWe | — | — |
| | [21] | NGNP | 4663$\$_{2009}$/kWe | — | — | 5899$\$_{2019}$/kWe | — | — |
| | [22] | NGNP | 5600$\$_{2018}$/kWe | — | — | 5932$\$_{2019}$/kWe | — | — |
| | [22] | HC-HTGR | 4550$\$_{2018}$/kWe | — | — | 4820$\$_{2019}$/kWe | — | — |
| | [22] | HC-HTGR | 3000$\$_{2018}$/kWe | — | — | 3178$\$_{2019}$/kWe | — | — |
| | [23] | MHTGR-SC | 3153$\$_{1992}$/kWe | — | — | 9900$\$_{2019}$/kWe | — | — |
| | [23] | MHTGR-SC | 2347$\$_{1992}$/kWe | 50$\$_{1992}$/MW-hr | 8$\$_{1992}$/MW-hr | 7370$\$_{2019}$/kWe | 157$\$_{2019}$/MW-hr | 26$\$_{2019}$/MW-hr |
| | [23] | MHTGR-GT/IC | 3290$\$_{1992}$/kWe | — | — | 10331$\$_{2019}$/kWe | | |
| | [23] | MHTGR-GT/IC | 2458$\$_{1992}$/kWe | 48$\$_{1992}$/MW-hr | 6$\$_{1992}$/MW-hr | 7718$\$_{2019}$/kWe | 151$\$_{2019}$/MW-hr | 19$\$_{2019}$/MW-hr |
| | [23] | MHTGR-GT/DC | 2656$\$_{1992}$/kWe | — | — | 8340$\$_{2019}$/kWe | | |
| | [23] | MHTGR-GT/DC | 1908$\$_{1992}$/kWe | 39$\$_{1992}$/MW-hr | 5$\$_{1992}$/MW-hr | 5991$\$_{2019}$/kWe | 123$\$_{2019}$/MW-hr | 16$\$_{2019}$/MW-hr |
| | [24] | HTGR | 5469$\$_{2017}$/kWe | 55$\$_{2017}$/MW-hr | — | 6068$\$_{2019}$/kWe | 62$\$_{2019}$/MW-hr | |
| **SFR** | [2] | SFR | 5632$\$_{2013}$/kWe | 113$\$_{2013}$/MW-hr | — | 6687$\$_{2019}$/kWe | 135$\$_{2019}$/MW-hr | |
| | [25] | 4S Sodium | — | 130-290$\$_{2009}$/MW-hr | — | | 165-367$\$_{2019}$/MW-hr | |
| | [26] | LSPB | 4734$\$_{2013}$/kWe | — | — | 5620$\$_{2019}$/kWe | | |
| | [27] | ABR1000 | 5612$\$_{2017}$/kWe | — | — | 6228$\$_{2019}$/kWe | | |
| | [28] | S-PRISM | 2664$\$_{2005}$/kWe | 39$\$_{2005}$/MW-hr | — | 5291$\$_{2019}$/kWe | 79$\$_{2019}$/MW-hr | |
| | [28] | S-PRISM | 3046$\$_{2005}$/kWe | 60$\$_{2005}$/MW-hr | — | 6050$\$_{2019}$/kWe | 120$\$_{2019}$/MW-hr | |
| | [29] | S-PRISM | 1334$\$_{1996}$/kW | 32$\$_{1996}$/MW-hr | — | 2650$\$_{2019}$/kWe | 65$\$_{2019}$/MW-hr | |
| | [28] | S-PRISM Mod B | 2073$\$_{2005}$/kWe | 39$\$_{2005}$/MW-hr | — | 4117$\$_{2019}$/kWe | 79$\$_{2019}$/MW-hr | |
| | [28] | S-PRISM Mod B | 2371$\$_{2005}$/kWe | 55$\$_{2005}$/MW-hr | — | 4709$\$_{2019}$/kWe | 111$\$_{2019}$/MW-hr | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | [30] | S-PRISM Mod B | $1554\$_{2004}$/kWe | $40\$_{2004}$/MW-hr | — | $3097\$_{2019}$/kWe | $89\$_{2019}$/MW-hr | |
| | [24] | LSPB | $4240\$_{2017}$/kWe | $80\$_{2017}$/MW-hr | — | $4705\$_{2019}$/kWe | $89\$_{2019}$/MW-hr | |
| **MSR** | [2] | AHTR | $5217\$_{2011}$/kWe | $111\$_{2011}$/MW-hr | — | $6425\$_{2019}$/kWe | $137\$_{2019}$/MW-hr | |
| | [2] | MSR | $6113\$_{2011}$/kWe | $119\$_{2011}$/MW-hr | — | $7529\$_{2019}$/kWe | $147\$_{2019}$/MW-hr | |
| | [2] | FHR | $5423\$_{2015}$/kWe | $135\$_{2015}$/MW-hr | — | $6198\$_{2019}$/kWe | $155\$_{2019}$/MW-hr | |
| | [31] | DMSR | $653\$_{1978}$/kWe | — | — | $4311\$_{2019}$/kWe | | |
| | [20] | AHTR | $3384\$_{2011}$/kWe | — | 34-60$\$_{2011}$/MW-hr | $4168\$_{2019}$/kWe | | 42-74$\$_{2019}$/MW-hr |
| | [24] | MSR | $3664\$_{2017}$/kWe | $51\$_{2017}$/MW-hr | $19\$_{2017}$/MW-hr | $4066\$_{2019}$/kWe | $57\$_{2019}$/MW-hr | $22\$_{2019}$/MW-hr |
| **Microreactor** | [32] | Reference micro-reactor | $10000\$_{2019}$/kWe | $150\$_{2019}$/MW-hr | $69\$_{2019}$/MW-hr | $10000\$_{2019}$/kWe | $150\$_{2019}$/MW-hr | $69\$_{2019}$/MW-hr |
| | [32] | Reference micro-reactor | $15000\$_{2019}$/kWe | $310\$_{2019}$/MW-hr | $103\$_{2019}$/MW-hr | $15000\$_{2019}$/kWe | $310\$_{2019}$/MW-hr | $103\$_{2019}$/MW-hr |
| | [32] | Reference micro-reactor | $20000\$_{2019}$/kWe | $410\$_{2019}$/MW-hr | $137\$_{2019}$/MW-hr | $20000\$_{2019}$/kWe | $410\$_{2019}$/MW-hr | $137\$_{2019}$/MW-hr |
| | [32] | Reference micro-reactor | $3996\$_{2019}$/kWe | $80\$_{2019}$/MW-hr | — | $3996\$_{2019}$/kWe | $80\$_{2019}$/MW-hr | — |
| | [32] | Reference micro-reactor | $8276\$_{2019}$/kWe | $200\$_{2019}$/MW-hr | — | $8276\$_{2019}$/kWe | $200\$_{2019}$/MW-hr | — |
| | [32] | Reference micro-reactor | $14973\$_{2019}$/kWe | $340\$_{2019}$/MW-hr | — | $14973\$_{2019}$/kWe | $340\$_{2019}$/MW-hr | — |
| | [33] | Design A | $65445\$_{2017}$/kWe | $2174\$_{2017}$/MW-hr | $112\$_{2017}$/MW-hr | $72611\$_{2019}$/kWe | $2413\$_{2019}$/MW-hr | $125\$_{2019}$/MW-hr |
| | [33] | Design A’ | $19241\$_{2017}$/kWe | $363\$_{2017}$/MW-hr | $122\$_{2017}$/MW-hr | $21348\$_{2019}$/kWe | $403\$_{2019}$/MW-hr | $136\$_{2019}$/MW-hr |
| | [33] | Design A’ | $6575\$_{2017}$/kWe | $135\$_{2017}$/MW-hr | $53\$_{2017}$/MW-hr | $7295\$_{2019}$/kWe | $150\$_{2019}$/MW-hr | $59\$_{2019}$/MW-hr |

# APPENDIX B

## Detailed Reactor Cost Estimates Breakdown

@This section highlights some of the more detailed estimates for reactor costs that were leveraged in Section 2.7. Additional background on the second level COAs is provided:

- **21 Structure and improvement**: This account includes the onsite surface buildings and structures and subsurface foundations and tunnels, that house and support all equipment, components, piping, ducting, and wiring. Also included in this account are site improvements, such as excavation, grading, roadways and railroads. In particular, substructure and superstructure details, architectural features and treatment of floors, walls, roofs, doors and glazing may be found in this account. The sub-accounts also include equipment and piping for the heating, ventilating and air conditioning systems, piping for the roof, floor and sanitary drains, and equipment for the lighting and service power (120 volt ac) systems for that structure. Nuclear power plants have two basic classes of onsite structures. Certain structures support and protect SR equipment and assist in the prevention of significant release of radioactivity to the environment.
- **22 Reactor plant equipment**: This account includes the equipment that liberates thermal energy from a fuel and uses the resulting heat to generate steam. For each reactor or boiler, support equipment is included to control the plant output, store an inventory of fuel, pretreat the fuel before actual burning (in the case of fossil power plants) and store and treat the residue or waste products. For a nuclear power plant, this equipment includes the reactor safety systems, the fuel storage systems, and the radioactive waste handling systems. The account includes the interconnecting piping systems, structural supports for equipment, and the necessary instrumentation and control systems.
- **23 Turbine plant equipment**: The turbine plant includes the power conversion system equipment that produces electric power from the steam generated by the reactor. All of the EEDB technical models use a conventional steam-turbine-generator unit. This account includes the turbine-generator unit, the condenser, the systems to purify and return the condensate to the reactor (condensate and feedwater systems) and the elevated turbine-generator pedestal. The account also includes the main vapor piping system, auxiliary support systems, interconnecting piping systems, structural supports for equipment, and the necessary instrumentation and control systems.
- **24 Electric plant equipment**: The electric plant includes the systems and equipment required to deliver the generated electric power to the utility's step-up transformer and offsite transmission system, provide auxiliary electric power for all power plant equipment and auxiliaries, and provide standby power for safety systems for nuclear power. The major sub-accounts are those for the cable and raceways for all power, control and instrumentation systems. This account also includes structural supports for equipment, the generator control system equipment and the plant grounding, lightning protection, freeze protection and cathodic protection equipment. For nuclear power plants, the most critical electric systems are designated "Class 1E." These are systems that are essential to the prevention of significant release of radioactivity to the environment.
- **25 Miscellaneous plant equipment subtotal**: This account contains the auxiliary mechanical and electric equipment required for normal power plant start-up, O&M. This includes the transportation and lift equipment (cranes), equipment in the air, water and steam service

system, the auxiliary boiler, the fire detection and protection systems, the communication system, the non-radioactive wastewater treatment system, various plant monitoring systems, and miscellaneous furnishings and fixtures. The account also includes the necessary interconnecting piping systems and structural supports for equipment.

- **26 Main condenser heat rejection system**: This account includes the equipment and associated structures that dispose of the heat rejected by the power plant and provide make-up water to the power plant. The systems are designed to dissipate the "excess" heat and provide the make-up water in such a way that harmful effects to the environment are minimized. The current power plants described by the EEDB technical data models use a closed, circulating water cooling system with wet natural draft cooling towers to dissipate the waste heat. The largest source of waste heat, usually accounting for 90 percent of the total, is the main steam-turbine condenser. The account also includes structures, equipment, and interconnecting piping systems for obtaining and pretreating the plant make-up water.

Table 19: Summary of two-digits code of account and their descriptions

| Code of Account (COA) | Descriptions |
|---|---|
| 21 | Structure and improvement |
| 22 | Reactor plant equipment |
| 23 | Turbine plant equipment |
| 24 | Electric plant equipment |
| 25 | Miscellaneous plant equipment |
| 26 | Main Condenser Heat Rejection System |
| 30 | Total indirect cost |

## B.1. Advanced PWR

This section compares two types of PWR: Large reactors, including PWR 12 and AP1000, and small modular reactors, including NuScale iPWR. PWR 12 is a single-unit 1144 MWe PWR described in EEDB [62]. All number are escalated to 2019 based on the cost factors discussed in table 3 [64]. The median of estimates from literature is listed. Two-digit costs from reference [17] are not included in the following table.

| | Median ($\$_{2019}$) | Range of capital costs ($\$_{2019}$/kWe) | Ref |
|---|---|---|---|
| 21 Structure and improvement | 594 | 555–897 | [17], [2], [20] |
| 22 Reactor plant equipment | 859 | 736–1097 | [17], [2] , [20] |

|  |  |  |  |
|---|---|---|---|
| 23 Turbine plant equipment | 620 | 480–610 | [17], [2] , [20] |
| 24 Electric plant equipment | 230 | 184–353 | [17], [2] , [20] |
| 25 Miscellaneous plant equipment | 134 | 130–210 | [17], [2] , [20] |
| 26 Main Condenser Heat Rejection System | 142 | 110–168 | [17], [2], [20] |
| 30 Total indirect cost | 1,576 | 1,051–3,967 | [2], [15] [20] |

All references with cost estimates for 2-digit accounts report similar costs for each account. Holcomb et al. [20] suggested that the Gen IV cost of accounts for indirect costs differs significantly from the EEDB accounts. In their work, the EEDB 91, 92, and 93 are mapped into the Gen IV accounts. Account 31 contains data from EEDB account 921. Account 32 consists of EEDB accounts 922 and 923. No EEDB data appears to map into account 33. Account 34 contains data from EEDB account 933, and account 35 contains EEDB data from account 932. Account 36, field indirect costs, has data from EEDB accounts 911, 912, 913, 924, and 931. Account 37 contains EEDB account 934. There is no data for account 38 demonstration run. This study recommends using estimates from EEDB database as reference.

## B.2. HTGR

This section compares four types of HTGR: next generation nuclear plant (NGNP), modular integrated gas high-temperature reactor (MIGHTR), Modular High-Temperature Gas-Cooled Reactor (MHTGR), and horizontal compact HTGR (HC-HTGR). NGNP is a pre-conceptual design with integration of high-temperature reactor technology with advanced hydrogen, electricity, and process heat production capabilities [65]. MIGHTR is proposed by Stewart et al. [17] with reactor core and steam generator horizontal and axially aligned. This novel layout allows for a much smaller confinement building without the need for overhead cranes during construction. MIGHTR is later extended to HC-HTGR by Stewart et al. [22] The horizontal layout reduces the HTGR costs and makes it economically competitive with AP1000 or a traditional four-loop PWR. However, the new layout could cause thermal stratification of helium coolant, overheating core internals and causing asymmetric thermal expansion, while more heats in the traditional HTGR can be carried from the cavity to the tank through natural circulation because of the RCCS comprises long vertical water panels in the cavity, connected to a water storage tank. MHTGR is designed based on generic gas-cooled reactor experience by combining any number of 350 MWth reactor modules in parallel with a selected number of turbine plants in a variety of arrangements. Basic features of HTGR of ceramic fuel, helium coolant, and graphite are sized and configured to provide a low power density core with passive safety features such that no operator action or external source of power is needed for the plant to meet criteria. Along with the reference steam cycle, detailed cost estimates of two MHTGR gas turbine concepts with direct and indirect helium gas cycles are investigated in reference [23].

|  | Median ($\$_{2019}$) | Range of capital costs ($\$_{2019}$/kWe) | Ref |
|---|---|---|---|
| 21 Structure and improvement | 722 | 419–3,268 | [17], [2], [22] [23] |
| 22 Reactor plant equipment | 1,851 | 1,288–3,891 | [17], [2], [22] [23] |
| 23 Turbine plant equipment | 889 | 557–1,730 | [17], [2], [22] [23] |
| 24 Electric plant equipment | 277 | 212–1,225 | [17], [22] [23] |
| 25 Miscellaneous plant equipment | 182 | 106–1,251 | [17], [2], [22] [23] |
| 26 Main Condenser Heat Rejection System | 132 | 96–289 | [17], [22] [23] |
| 30 Total indirect cost | 1,745 | 1,745 | [2] |

We observed that HTGRs with higher power outputs generally have lower costs than those with lower outputs. The HC-HTGR (MIGHTR) results in lower costs (20% less) than NGNP. More specifically, the civil structure costs are reduced by 42% and indirect costs by 38%. For total specific costs, Stewart et al., Buongiorno et al., and Gandrik et al. presented similar values for NOAK NGNP (+/-20%). The total specific costs were much higher (>50%) for single units than four units. FOAK units presented much higher (>50%) costs than NOAK units. Although with similar total costs, Buongiorno et al. presented much lower total direct costs (4809 $\$_{2009}$/kWe) than Stewart et al. (2456 $\$_{2014}$/kWe). Such differences could be caused by the differences in structural and improvement costs (Buongiorno et al. 331 $\$_{2009}$/kWe vs. Stewart et al. 1436 $\$_{2014}$/kWe); Turbine plant equipment (Buongiorno et al. 478 $\$_{2009}$/kWe vs. Stewart et al. 809 $\$_{2014}$/kWe); no electrical plant equipment and condensing heat rejection costs in Buongiorno et al. Other factors like different technology maturation levels, IDC, and contingency costs could also result in different total costs. This study recommends using estimates from Gandrik et al. with 4 units 350 MWth and 750 C reactor outlet temperatures as the reference.

## B.3 SFR

This section compares three SFR designs: 1100 MWe reference SFR from EEDB 1988 based on the EMWG code of account; advanced burner reactor (ABR-1000); PRISM and related variations, including Super PRISM and PRISM Mod B. Details of reference SFR design from EEDB are currently unknown. ABR1000 is a 1000MWth/380MWe pooled type sodium cooled fast reactor. Compared to PRISM, PRISM Mod B achieves a 0.8 conversion ratio. The S-PRISM contains 4 units, while each unit generates 413 MWe. The PRISM Mod B has 6 units, and each unit produces 311 MWe. The DMSR has 1 unit.

|  | Median ($\$_{2019}$) | Range of capital costs ($\$_{2019}$/kWe) | Ref |
|---|---|---|---|

| | | | |
|---|---|---|---|
| 21 Structure and improvement | 396 | 281–796 | [2], [26], [28] |
| 22 Reactor plant equipment | 1,187 | 958–1,751 | [2], [26], [28] |
| 23 Turbine plant equipment | 386 | 281–568 | [2], [26], [28] |
| 24 Electric plant equipment | 187 | 119–402 | [26], [28] |
| 25 Miscellaneous plant equipment | 129 | 42–562 | [2], [26], [28] |
| 26 Main Condenser Heat Rejection System | | 0–562 | [2], [28] |
| 30 Total indirect cost | 1,000 | 344– 2,630 | [2], [26], [28] |

Shropshire [28] presented much lower costs (>50%) than Ganda et al. and Buongiorno et al. [2] Such major differences could result from completely different reactor designs, where Shropshire et al. estimates were based on PRISM SFR designs, while Ganda et al. and Buongiorno et al. were based on EEDB reference 1100 SFR.

Shropshire modified GE estimation [66], including updating dollars from 1996 to 2005 using U.S. Gross Domestic Product (GDP) deflator. Capacity factor is decreased from 93% to 86% to account for more frequent refueling in recycle mode. Cost of capital is changed from 9.16% to 10% following EMWG. Construction period is lengthen to 5 years, increasing IDC. Decommissioning is changed to EMWG standards, decreasing D&D sinking fund contribution. Shropshire also modified ANL (2004) [30] update dollars from 1994 to 2005 using U.S. GDP deflator. Cost of capital is changed from implicitly 9.44% to 10% following EMWG. The implicit building period is lengthen to 5 years, increasing IDC. Decommissioning is changed to EMWG standards. Increased preconstruction costs and contingency (16.7% to 20%).

Ganda et al. and Buongiorno et al. made similar costs (+/-20%). Some obvious differences include that Buongiorno et al. presented higher costs for miscellaneous plant equipment (473$\$_{2014}$) and condensing heat rejection (473$\$_{2014}$) than a combined 209$\$_{2013}$. Buongiorno et al. presented \$0 costs for electrical plant equipment, while Ganda et al. showed 157$\$_{2013}$.

In summary, more design information is needed to determine the reasonable costs for each account. This study recommends using estimates for ABR1000 from Ganda et al. [27].

### B.4. MSR

This section discusses capital costs of two MSR designs from three references, including the single-unit AHTR 3400 MWth/1350 Mwe based on 1100 Mwe PWR using ANL escalation basis for PWR 1100MWe [20] and Single-unit denatured MSR (DMSR) 1000 MWe with once-through fueling [31].

| | Capital costs ($_{2019}$) | Range of capital costs ($_{2019}$/kWe) | Ref |
|---|---|---|---|
| 21 Structure and improvement | 683 | 508–819 | [2], [20], [31] |
| 22 Reactor plant equipment | 1,040 | 886–1189 | [2], [20], [31] |
| 23 Turbine plant equipment | 537 | 470–661 | [2], [20], [31] |
| 24 Electric plant equipment | 270 | 190–357 | [2], [20], [31] |
| 25 Miscellaneous plant equipment | 127 | 113–196 | [2], [20], [31] |
| 26 Main Condenser Heat Rejection System | 109 | 76–140 | [2], [20], [31] |
| 30 Total indirect cost | 1,699 | 1,070–2,056 | [2], [20], [31] |

For AHTR 3400, Buongiorno et al. and Holcomb et al. made similar (+/-20%) direct and indirect cost estimates. However, Buongiorno et al. considered the contingency and IDC rates and resulted in 5217 $\$_{2011}$/kWe, comparing to the 3384 $\$_{2011}$/kWe by Holcomb et al. as shown in Table 1. For DMSR, Buongiorno et al. made higher estimates (>50%) than Engel et al. For example, the miscellaneous costs by Buongiorno are 159 $\$_{2014}$/kWe (escalated to 195 $\$_{2019}$/kWe) by Buongiorno et al. comparing to 17 $\$_{1980}$/kWe (escalated to 112 $\$_{2019}$/kWe) by Engel et al. This study recommends using AHTR costs from Holcomb et al. [20] as reference.