Quantifying Capital Cost Reduction Pathways for Advanced Nuclear Reactors

Systems Analysis & Integration Campaign

Prepared for
U.S. Department of Energy
Systems Analysis & Integration Campaign

Chandrakanth Bolisetti, Abdalla
Abou-Jaoude, Botros Hanna,
and Levi M. Larsen (INL)
Jia Zhou (ANL)
Koroush Shirvan (MIT)

June 6, 2024
INL/RPT-24-7767

SUMMARY

Capital cost considerations are one of the primary inhibitors to the large-scale deployment of nuclear power plants. While it is widely accepted that first plants will likely be expensive and relatively uncompetitive, it is reasonable to expect that subsequent plants, built in quick succession, will be cheaper as they benefit from the so-called "learning effects". However, the large degree of uncertainty associated with this parameter renders it challenging for first movers to invest in the first few expensive plants. To resolve this impasse, the U.S. Department of Energy's Advanced Nuclear Liftoff study advocated for the formation of large, committed order book of same-design plants to kickstart the nuclear supply chain (DOE 2023). The study also advocated best practices for avoiding overruns and keeping reactors on budget. This report builds on these key recommendations by attempting to quantify specific pathways toward cost reduction for nuclear energy.

A capital cost estimation framework was built to untangle the effect of learning into a subset of key cost drivers, referred to as "levers". Collectively, the choice of these levers is intended to reflect the decision-making of high-level stakeholders like plant owners and the government. In addition to the size of the firm order book, these levers included (a) cost drivers that are most often attributed to cost overruns such as architect/engineering (A/E) proficiency, construction proficiency, supply chain service proficiency, design completion prior to the start of construction, and design maturity, and (b) cost reduction strategies such as modular construction, cross-site standardization, safety classification of the reactor building, and of the balance of plant. Two advanced reactor concepts were leveraged as use cases and bottom-up cost estimates made with assumptions consistent with a well-executed first-of-a-kind project (WE-FOAK, i.e., almost no overruns). These were used as baselines for the models. Cost correlations were surveyed from the literature to determine the impact of important variables on projected timelines and costs.

The framework enables users to explore the impact of levers on the evolution of capital costs and capital investment from the first plant in the order book, which would be a first-of-a-kind (FOAK) plant, to the Nth plant in the order book, which would be an Nth-of-a-kind (NOAK) plant. In this study, the average capital cost of all the plants in the order book is used as a quantity of interest that is affected by various levers. None of the values estimated in the report should be interpreted to be absolute or deterministic in nature. Readers are referred to

Abou-Jaoude (2024) for nuclear technology cost projections. Rather, the framework built here allows for a quantifiable assessment of cost trends primarily for comparative purposes. The framework is implemented in a spreadsheet tool, which is provided as an attachment to this report, as well as a Python Notebook, which is included in the ACCERT software developed by the Systems Analysis and Integration (SA&I) campaign.

Using the framework, the report explored four possible scenarios for cost reduction from a FOAK plant with substantial overruns to NOAK plant that has little/no overruns and leverages the experience gained through repeated deployment of the same reactor type. The scenarios explored both optimistic (well-executed) and pessimistic (poorly executed) scenarios and how existing Investment Tax Credit (ITC) can be particularly influential for early deployments (US Congress 2023). Outputs for an example scenario are shown in Figure 1, which models an imperfect project execution for FOAK (within expectations for an advanced reactors), and ITC applied to the first plant. The figure shows the levers used to model this scenario, the resulting overnight capital cost (OCC) from FOAK to NOAK, and the reductions achieved from various levers and variables in the form of a waterfall chart. Additional scenarios (with different lever values selected) were also considered in this study with both advanced reactor concepts. Key findings from the results are as follows:

- Several pathways were identified to reach the DOE Liftoff report suggested target of $3,600/kWe for Nth plant OCC (DOE 2023). The larger challenge however was ensuring that the average cost across the order book was low enough to be cost-competitive. This is still shown to be achievable under various scenarios analyzed.
- In general, cost reductions of about 45-60% in OCC were estimated between the first and third plant deployed of a given reactor concept. This highlights the importance of multi-plant orders to drive down nuclear energy costs.
- Averaging nuclear reactor costs across an order book size of 13 or more plants (from FOAK to NOAK) can bring average costs within cost-competitive levels when starting with engineering procurement and construction (EPC) contractors with “medium proficiency”. The level of proficiency assigned to a contractor is based on user judgment and the framework developed here does not attempt to quantitatively assess different contractors.
- Only accounting for the second plant onwards (e.g., if the first plant demonstration is already being executed such as in the two already-sponsored DOE Advanced Reactor Demonstrations) can drastically reduce average costs and facilitate the cost reduction pathways. To reach cost-competitive average OCC values, the number of plants in the case described above can be dropped from 13 to 6 plants if the cost of the first plant is not accounted for.
- On the other hand, a much larger order book (~18 plants) will be needed to compensate for the overruns due to poor executions of the first plant (e.g., from poor construction proficiency and/or rushing to

build it prior to design completion) and bring the average net OCC down to cost-competitive levels for a specific reactor design.

- Very good execution of the first plant (with tax credits applied) can lead to cost-competitive average costs with an order book as small as 6 plants.
- If the first four plants can be built within the current timeline of the Inflation Reduction Act (IRA) and claim 40% of ITC (US Congress 2023), the average net OCC (OCC with ITC included) can reach cost-competitive levels despite poor executions of the first few plants.
- Optimistic scenarios involving upfront investment in reducing the first plant costs (such as starting construction after more than 90% design completion, choosing contractors with higher proficiency, etc.) can bring the order book-averaged overnight capital cost as low as the DOE Liftoff NOAK target (DOE 2023). At these cost ranges nuclear energy would be poised to be very competitive across the United States as highlighted by the DOE Liftoff report.
- A staggered timeline with 75% overlap between subsequent plant builds was assumed in this study. This level of overlap is anticipated to provide nearly optimal learning between plant builds. With these assumptions, a buildout of 4 plants is expected to require between 9-15 years for the optimistic scenario depending on the reactor concept.
- A sensitivity analysis conducted on all the levers considered in this study found that the order book size, interest rates, standardization, and EPC proficiencies have the largest impact on averaged capital costs (in that order). Overall, the benefit of reducing cost overruns in the first 4-5 plants overshadows the cumulative cost reduction achieved from experience-based efficiency in the last few plants, emphasizing the need for good project execution.
- Ultimately many of these conclusions depend on the reactor and plant design. The power capacity, ratio of factory/site activities, plant layout, and other specifications of a reactor concept will also influence the potential for cost reductions. However, the impact of design-dependent factors on cost reductions were not fully quantified in this study.

This framework relies on several simplifying but informed assumptions and is not without limitations. It could benefit from several improvements in the future. Nevertheless, it provides an important tool for stakeholders to visualize the benefits of creating a firm order book of advanced nuclear plants and the influence of high-level decision making on the average cost of the order book.

Number of Firm Orders	13
Interest Rate	6%
Design Completion	80%
Design Maturity (0, 1, 2)	1
Supplychain Proficiency (0 - 2)	0.5
A/E Proficiency (0 - 2)	0.5
Construction Proficiency (0 - 2)	1
Cross Site Standard-ization	80%
Modular Civil Construction	TRUE
Commercial BOP	TRUE
Non-Safety-Related RB	FALSE
ITC Amount	40%
Numbers of units with ITC	1

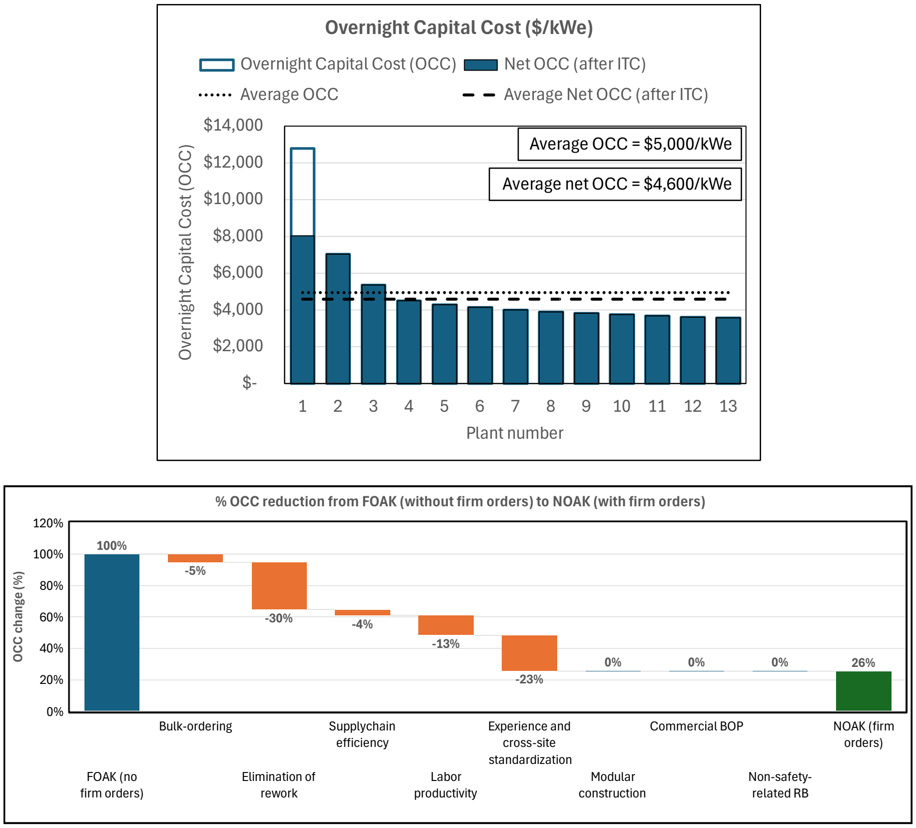


Figure 1. Illustration of the quantitative framework for nuclear power plant capital cost reduction developed in this report.

Page intentionally left blank

ACKNOWLEDGMENTS

This report was authored at Idaho National Laboratory (INL) 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 through the Systems Analysis & Integration (SA&I) Campaign.

The authors would like to thank the following colleagues for their valuable comments, reviews, and suggestions:

- Andrew Foss, Brent Dixon, and Jason Hansen (INL).
- Taek K. Kim and Nicolas Stauff (ANL).
- Bhupinder Singh and Jason Marcinkoski (DOE).

The authors would also like to thank Rebecca Ritter (INL) for her comprehensive editorial review of the report.

Page intentionally left blank

CONTENTS

FIGURES

TABLES

Page intentionally left blank

ACRONYMS

ACCERT	Algorithm for the Capital Cost Estimation of Reactor Technologies
ARDP	Advanced Reactor Demonstration Program
BOP	Balance of Plant
CANES	Center for Advanced Nuclear Energy Systems
CEPCI	Chemical Engineering Plant Cost Index
COA	Code of Accounts
COLA	Construction and Operating License Application
DOE	U.S. Department of Energy
EEDB	Energy Economic Data Base
EMANES	Economics and Market Analysis for Nuclear Energy Systems
EMWG	Economic Modeling Working Group
EPC	Engineering Procurement and Construction
EPRI	Electric Power Research Institute
ESP	Early Site Permit
FERC	Federal Energy Regulatory Commission
FOAK	First-of-a-Kind
FY	Fiscal Year
GIF	Generation IV International Forum
GN-COA	Generalized Nuclear Code of Account
HALEU	High-Assay Low-Enriched Uranium
HTGR	High-temperature Gas-cooled Reactor
HVAC	Heating, Vent, and Air Conditioning
IAEA	International Atomic Energy Agency
I&C	Instrumentation & Control
IDC	Interest During Construction
INL	Idaho National Laboratory
INPO	Institute of Nuclear Power Operations
IRA	Inflation Reduction Act
ITC	Investment Tax Credits
LR	Learning Rate
LWR	Light-Water Reactor
MARVEL	Microreactor Applications Research Validation and Evaluation
MIT	Massachusetts Institute of Technology

MRP	Microreactor Program
NCET	Nuclear Cost Estimating Tool
NCI	Net Capital Investment
NEI	Nuclear Energy Institute
NGNP	Next Generation Nuclear Plant
NOAK	Nth-of-a-Kind
NPP	Nuclear Power Plant
NSSS	Nuclear Steam Supply System
O&M	Operation and Maintenance
OCC	Overnight Capital Cost
PRISM	Power Reactor Innovative Small Module
PWR	Pressurized-Water Reactor
RB	Reactor Building
ROT	Reactor Outlet Temperature
SA&I	Systems Analysis and Integration
SC	Steel Composite
SFR	Sodium-cooled Fast Reactors
SMR	Small Modular Reactor
TCI	Total Capital Investment
TRISO	Tristructural Isotropic Particle
VCE	Vibrant Clean Energy
VHTGR	Very High-Temperature Gas-cooled Reactor

QUANTIFYING CAPITAL COST REDUCTION PATHWAYS FOR ADVANCED NUCLEAR REACTORS

1. INTRODUCTION

Interest in nuclear energy has surged recently in light of its ability to provide reliable, carbon free, firm energy. Utilities and states across the United States are taking another look at power sources and considering the deployment of new advanced reactors. A Systems Analysis and Integration (SA&I) campaign report indicated that in a net-zero emissions scenario, the U.S. nuclear capacity in 2050 will need be more than twice the current nuclear fleet (Kim, 2013). More recently, the U.S. Department of Energy (DOE) Liftoff report highlighted the potential for 200 GW of new nuclear deployment by 2050 (DOE 2023). A key impediment hindering the ability of nuclear energy to reach these levels of deployment is its capital cost (Buongiorno 2018). With an unestablished supply chain and limited construction experience, capital costs are particularly expected to be high for the first-of-a-kind (FOAK) demonstration. However, as more plants are built and experience is gained, these costs are expected to decrease. It is difficult to quantify these expected cost reductions as they depend on a wide variety of factors, some of them outside the project control. Nevertheless, being able to provide a more quantifiable basis for pathways toward capital cost reductions could help provide decision-makers with greater certainty on the path to reaching competitive nuclear energy.

This is the main purpose of this report for the Department of Energy Office of Nuclear Energy (DOE-NE) Systems Analysis & Integration (SA&I) campaign. The report intends to quantify parameters that influence nuclear costs to untangle the biggest contributors of cost reduction from FOAK to NOAK (often grouped together and loosely quantified as a parameter called "learning") into subcomponents. By doing so, the study aims to establish a stronger basis for projecting cost reductions in nuclear reactors. As identified by the DOE Advanced Nuclear Liftoff study, utilities and other NPP owners forming a consortium and placing a large, committed order book of nuclear plants of one kind (as opposed to each utility or owner placing their own separate order) and sharing the financial risk involved in building the first few plants can catalyze commercial liftoff in the United States (DOE 2023). Indeed, a three-utility collaboration focused on deployment of a single reactor design has already been formed.[a] However, the feasibility and financial mechanisms required to establish such a consortium are outside the scope of this study. This report instead develops a capital cost estimation framework that can explicitly quantify the impact of this order book size as well as various other cost driving parameters on cost projections for nuclear energy. The framework uses the term "levers" to represent and quantify these parameters that include both cost drivers such as incomplete design before starting construction, proficiency of construction or supply chain services, as well as cost reduction approaches such as modularity and standardization. These levers are often intercorrelated and can have an integrated impact on cost and schedule. Several studies such as Buongiorno (2018), OECD (2020), and Stewart (2023) identify a comprehensive set of cost drivers, many of which are adopted in this study. Values for the levers in the framework can be specified by the end-user (target audience includes utilities, energy users, reactor vendors, or policymakers). In this report, bottom-up tools and empirical evidence was used to help inform these inputs in the various scenarios considered. These inputted lever values are then used to modify a "baseline" cost estimate based simple correlations to calculate the evolution of capital costs of the plants in the order book from FOAK to NOAK. The hope is this work will help unblock first movers who are hesitant to build the FOAK by demonstrating a realistic progression of nuclear costs.

The analysis portion is divided into three main parts. In Section 2, a background on nuclear cost evolution and cost reduction is surveyed and summarized, including key references leveraged in the

---

[a] https://www.tva.com/newsroom/press-releases/tennessee-valley-authority-ontario-power-generation-and-synthos-green-energy-invest-in-development-of-ge-hitachi-small-modular-reactor-technology

analysis. Section 3 describes the methodology underlying the development of the cost reduction framework. This includes correlating cost values (i.e., accounts) to individual levers such as construction proficiency, that are input by the user. Starting with a baseline cost, projected cost evolutions from an FOAK to an NOAK plant in the order book are quantified allowing users to tune the levers and identify different pathways toward cost reduction. Order book-averaged cost is also used as a quantity of interest that represents the "collective" investment for several plants. In Section 4 of the report, this framework is used to simulate various scenarios that can lead to competitive, order book-averaged prices for nuclear energy. A high-level overview of the scope is provided in Figure 2.

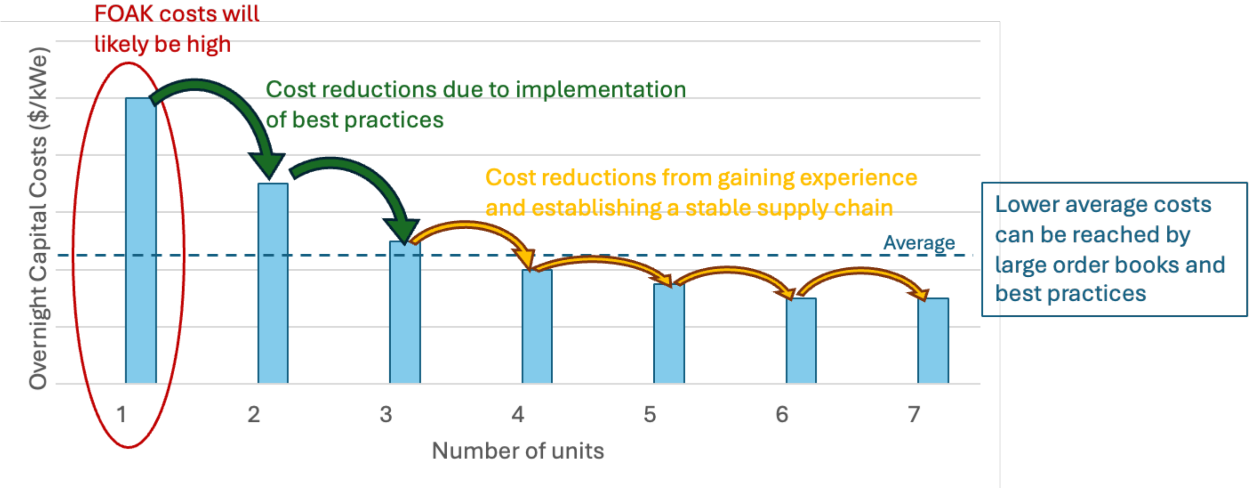
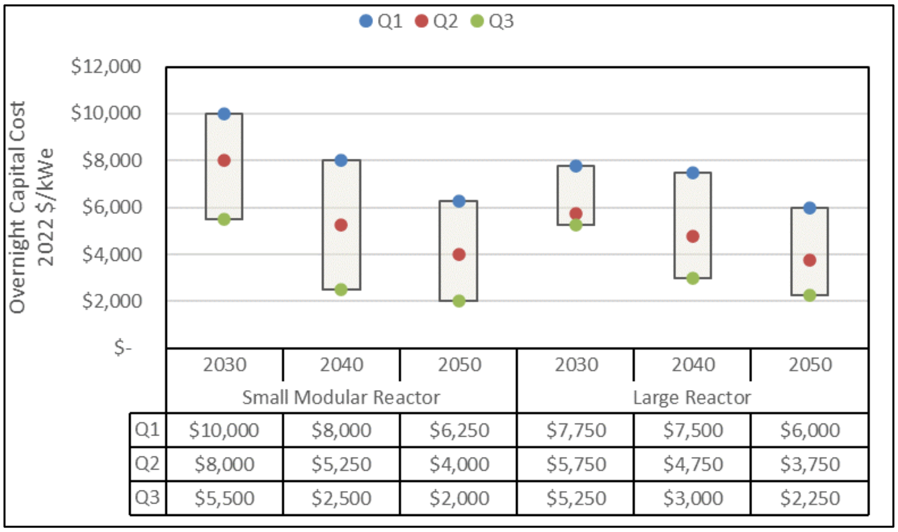


Figure 2. Illustration of the framework developed in this report. By correlating costs to cost driving parameters called levers, projections of cost evolutions over plants of deployments can be quantified. This enables the ability to identify possible pathways toward a set target average price for the set of new reactors deployed.

Ultimately, the framework built in this report is expected to be a useful tool for decision makers to evaluate possible pathways and anticipate challenges to reach competitive costs for nuclear energy. It is not intended to provide reference cost estimates, but rather to showcase possibilities for cost reductions. Readers interested in reference cost projections for nuclear reactors (e.g., to use in capacity expansion models) are instead directed to Abou-Jaoude (2023). Figure 3 provides a summary graph from that study, along with the recommended overnight capital cost (OCC) ranges under conservative, moderate, and advanced conditions for nuclear energy. Notably, the study highlights the potential for substantial cost reductions beyond the number of plants considered in this study (typically in the 5–20 plant range whereas Abou-Jaoude (2023) considered scenarios with up to 200 GW of new nuclear deployed potentially involving hundreds of plants).

This report also does not intend to replace professional, project-specific cost estimates, such as the Class I-V estimates defined by AACE (AACE International, 2020). The validity of costs calculated relies on the underlying data, correlations, and assumptions, which can be subjective for some parameters and also be updated as more data is available. It also should not be interpreted as a comprehensive evaluation of all potential pathways and levers. Instead, it should be viewed as a best effort estimate based on existing literature and data to project nuclear energy cost evolutions. With the foundation for quantifying different pathways for cost reduction established via this framework, future work could refine the methodology, estimates, and capabilities summarized here to achieve greater cost certainty for stakeholders.



	Small Modular Reactor 2030	Small Modular Reactor 2040	Small Modular Reactor 2050	Large Reactor 2030	Large Reactor 2040	Large Reactor 2050
Q1	$10,000	$8,000	$6,250	$7,750	$7,500	$6,000
Q2	$8,000	$5,250	$4,000	$5,750	$4,750	$3,750
Q3	$5,500	$2,500	$2,000	$5,250	$3,000	$2,250

Figure 3. Recommended OCC ranges for large and small reactors in Abou-Jaoude 2024.

2. BACKGROUND ON PREVIOUS WORK

A wide array of references in the open literature have attempted to quantify the main drivers behind nuclear costs and potential opportunities for cost reduction. This section provides a brief background on various relevant studies that evaluated nuclear energy cost dynamics, with an emphasis given to references that were further leveraged in later parts of the report to drive relationships.

First efforts to systematically study nuclear energy costs and its constituents can be traced back to the Energy Economics Database (EEDB) effort in the 1980s (DOE 1987a, 1987b, 1987c, 1988a, 1988b). This study evaluated a broad data set of detailed NPP cost estimates (consisting mainly of LWRs and some non-LWR concepts, e.g., liquid-metal cooled reactors) in the United States. It compiled a broad range of observed costs for reference designs and organized them into a detailed code-of-account (COA) structure. The study then evaluated several trends in the data (e.g., comparing the best experience with the median experience for costs) and quantified several correlations that drive costs. The report has served as the basis for many subsequent studies. Most notably, the SA&I campaign developed a family of cost algorithms to link costs to design parameters and manipulate the data to evaluate the impact of new reactor and plant concepts (Ganda 2017, 2018, 2019). This methodology of developing cost algorithms was termed the ACCERT methodology, which is now implemented in the ACCERT software (Zhou, 2023 and Bolisetti 2023), also developed by the SA&I program. Similarly, the Massachusetts Institute of Technology (MIT) has developed its own set of tools also based on the EEDB to quantify FOAK to NOAK capital costs, construction schedule, and risk for cost overruns (Stewart 2022a, 2022b, 2022c, 2023). MIT has applied this tool to water-cooled and gas-cooled small and large reactors.

Typically, when attempting to project nuclear cost evolution, studies have relied on the learning rate equation, which is widely used in the nuclear and non-nuclear industries to represent the evolution of costs as more units are produced. Learning rate is the percentage cost reduction for each doubling of units deployed (Wright, 1936; Mislick and Nussbaum, 2015). Estimates on learning rate values for nuclear reactors vary greatly within the literature. The approach followed to determine rates from observed builds and account for the impact of other variables (e.g., change in regulatory regime) varied greatly among sources. For instance, several studies leveraged a top-down approach that used information from past- and new-build nuclear reactors and other renewable technologies on costs and experience (Mooz 1979; Komanoff 1981; McCabe 1996; McDonald 2001). Others relied solely on observed data without any further manipulation. For instance, South Korea pursued a deployment schedule of roughly two reactors every 2 years between 1995 and 2011 with minimal changes in external factors. As a result of this deployment rate, reductions in construction cost of 63% relative to FOAK were observed (Lovering 2016).

While learning rate values for large reactors based on observed costs are often debated in the literature, values for small modular or advanced reactors are even more uncertain, primarily because these reactors have never been built and therefore, cost data for these plants does not exist. Several studies have attempted to project potential learning rates that can be expected for these smaller reactor variants. Many studies used top-down approaches based on values for larger reactors (VCE 2022; Boldon 2014; Lyons 2019; Peres 2017). The majority of this group of studies attempted to quantify the impact of modularization and shifting of more activities to the factory to correct observed learning rates for larger reactors. On the other hand, some evaluations have attempted to evaluate cost evolutions from the bottom-up (Atkins 2016; Stewart 2020; Abou-Jaoude 2021). Cost evolutions are defined for individual subcomponents of the costs to then derive a higher-level overall learning rate for a given design. Overall, it appears that the consensus is that small modular reactors (SMRs) are expected to have faster learning rates than their larger counterparts and this is attributed to increased modularity and offsite work through factory fabrication.

The lack of granularity with quantifying learning rates as well as the great degree of associated uncertainty led this report to attempt to untangle the underlying effects leading to such learning rates. As such, it was important to evaluate studies that specifically addressed drivers for cost reductions/overruns. Insights from the previously highlighted references that conducted bottom-up learning rate evaluations are used as a starting point for this study. It should be noted that there are more than a hundred or so cost studies that have attempted to document, understand, and analyze nuclear costs with various techniques over the last few decades. Not all these studies were reviewed here. Refer to Lovering (2016), EPRI (2019), and Eash-Gates (2020) for a comprehensive review of these studies.

One of the early efforts in understanding nuclear cost drivers was a DOE report (Hewlett 1986). This report leveraged a sample of nuclear power plants that entered construction during the 1966–1977 period to statistically analyze the nuclear power plant construction costs and construction periods. The statistical analysis included variables such as the construction wages, the utility nuclear experience, the number of plants, the effect of stop-work orders, and the impact of the architecture-engineering experience on the on the capital cost. This report concluded that 75% of the cost overruns was attributed to increases in labor, material, and equipment costs while the remaining 25% was related to increases in the financing charges. The report also emphasized the impact of the construction duration length on the cost changes. Eash-Gates (2020) analyzed cost data from EEDB and quantified factors such as regulatory interference (referred to as "process interference, safety" in the paper), research and development, and worker and material productivity. This study also documented the effect of "worsening despite doing", which essentially is an increase in cost over time even when building similar reactor designs, indicating that, historically, there has been a lack of adequate design standardization across sites.

Perhaps the most similar to the present study is the 2019 EPRI report (Marciulescu 2019), which developed a cost estimation tool that takes construction-related cost drivers such as civil/structural design costs, constructability of the design, material and labor costs, regulatory requirements, and many others to estimate the costs. Using an approach similar to the present study, they found that if existing technologies can be used to address five main cost drivers—constructability of design, civil/structural design, construction materials, craft labor cost, and inspection—the OCC can be reduced to around $3,421/kWe. The present study leveraged several results and insights from this study, including construction duration and design completion as significant cost drivers and their correlations with OCC.

Since 2021 Stewart and Shirvan developed another notable cost estimation framework (called TIMCAT) through a series of works that studied different small and large reactor architectures constructed with and without modular installation. These previous studies applied a more bottom-up learning model for material (7%), onsite labor (13%), and factory activities (16%). For mature components, a high number of existing of units was used in the standard learning model to limit the impact of cost reduction from FOAK to NOAK. The TIMCAT tool was benchmarked against realized projects including the AP1000s in the United States and China (Shirvan 2022) and advanced boiling-water reactors which were constructed in record time (about 3 years) in Japan (Stewart 2022a). The study found that reactor architecture does make a significant impact on cost (>30%). For overnight capital cost, mass of steel per MW and power density of nuclear island were key cost drivers. In general, modular construction was found to be very effective in reducing construction schedule; however, no benefit on cost and schedule was observed for FOAK plant. The work highlighted that despite more dependence on factory production, SMRs were still projected to realize on average higher onsite labor per MW than large reactors and exhibited megaproject characteristics (in terms of scale, i.e., costs larger than $1 billion, and project complexity). Under labor-constrained scenarios (i.e., lack of access to large, trained construction work force), economy-of-multiples (reduction in cost achieved through building several plants and leveraging learning) can balance lack of economy-of-scale for SMRs when installing few GWe of nuclear energy.

Many of the studies have analyzed direct costs, but indirect costs tend to also be at least an equally important (or more important in the case of poorly executed projects) driver of nuclear costs. Indirect costs consist of construction support activities such as engineering, administration, construction services, construction management, field supervision, startup, and testing (Ganda 2016). Historical trends within the EEDB indicate that indirect costs for FOAK plants have typically been substantially higher than those for NOAK plants. For example, PWR12-BE (better experience) indirect costs calculated in EEDB were nearly half the direct costs, while PWR12-ME (median experience) had indirect costs equivalent to direct costs (DOE 1987a, 1987b, 1987c, 1988a, 1988b). FOAK plants tend to encounter inflated indirect costs due to longer construction timelines, which necessitate the protracted use of rental equipment and temporary facilities. Regulatory evolutions also intensify these costs by imposing additional requirements on QA/QC, field supervision, and engineering services. Ideally, an assessment of indirect costs extends beyond simple tabulation and requires more knowledge of site labor demands, workforce numbers, and project schedules (Stewart 2022a). Such analysis requires robust, precise methodologies for estimating construction timelines across different reactor designs. This reality dictates that the traditional model of calculating indirect costs by applying a static multiplier to direct costs is inadequate. Instead, a more dynamic approach is required, incorporating the specific conditions of each project, including reactor design, construction schedule, and regulatory demands. A refined calculation approach assigns fractions of total indirect costs to the plant components then sums up the share of indirect costs (Eash-Gates 2020, Stewart 2023). Another study derived a mathematical modeling of the relationship between construction duration and indirect costs from historical project analyses (Asuega 2023).

The study presented in this report aims to perform a bottom-up quantification of cost overruns and, therefore, possible cost reductions from a FOAK plant to a NOAK plant. As described in this section, many studies have attempted to quantify cost drivers and their contributions, primarily with an intention of improving plant designs and construction execution. However, given the primary audience of this study is stakeholders and decision-makers, this study takes a different approach and attempts to quantify the impact of high-level decisions such as government support, choice of contractors for design and execution, etc., on costs. More importantly, it also attempts to quantify the impact of nuclear plant buyers placing a large, firm order book that can jump start a supply chain, a trained work force, and share the risk of overruns in the first few builds.

3. DEVELOPMENT OF THE COST REDUCTION FRAMEWORK

The goal of the cost reduction framework is to model the evolution of nuclear capital costs from a FOAK to a NOAK project. This evolution depends on a set of levers that stakeholders, such as utilities, reactor vendors, or governments, can use to influence the FOAK cost or at the speed that NOAK cost reduction is achieved. The cost reduction framework therefore inputs a baseline cost estimate along with a set of levers and outputs the expected costs of the FOAK project, second of a kind, and so on until NOAK, as shown in Figure 2.

Perhaps the largest impediment to taking advanced nuclear from FOAK to NOAK costs is the financial risk of incurring FOAK cost overruns and associated project risks due to a lack of a mature supply chain or a workforce. The novelty of advanced nuclear technologies will require technology-specific development. As identified by the DOE Advanced Nuclear Liftoff study, a key to de-risking the first buyer is through the energy industry, including utilities and other energy buyers (e.g., owners of data centers and chemical plants) to collectively create a committed order book: a firm financial commitment to buy a number of plants of one technology so that it provides vendors enough confidence to invest a significant capital into developing a supply chain and a workforce (DOE 2023). The cost reduction framework therefore lays particular emphasis on the idea of a firm order book and determines the progression of FOAK to NOAK costs, with "N" as the order book size. Additionally, only capital costs are considered since they are the primary driver of the initial investment in nuclear. It is important to mention that while the framework is quantitative in nature, the results shown here should not be interpreted as 'definitive' projections of nuclear costs. These will be very project dependent and will require a dedicated professional cost estimation to be conducted.

The rest of this section describes the cost reduction framework in detail. Section 3.1 describes the basic components of the framework, and Section 3.3 describes how these components are related and the underlying assumptions that are used to derive these relationships. The framework is developed and implemented both in a spreadsheet tool and a Python Jupyter notebook (included in the ACCERT software developed by SA&I) in an identical fashion. Currently, the framework is implemented for two advanced reactor concepts. The baseline cost estimates used for these technologies are described in Section 3.2. The framework can also be implemented to model cost evolutions of other reactor technologies with minimal additional effort. The spreadsheet version of the framework can be downloaded at: https://fuelcycleoptions.inl.gov/Shared%20Documents/Nuclear-Reactor-Capital-Cost-Reduction-Pathway-Tool.pdf

3.1 Components of the Framework

The main parameters of the framework are levers, variables, and accounts. Accounts refer to the cost items in the COA system, which is used to organize costs in most technoeconomic studies. The generalized-nuclear COAs (GN-COA) system (Moneghan 2024) is followed in this study. Variables are endogenous parameters that impact the cost accounts directly such as amount of rework and labor productivity. Levers are exogenous parameters such as government support and proficiency of contractors that can be influenced by stakeholders like the government and plant owners. The framework is set up so that for each baseline cost estimate, a user can adjust the levers to their choosing (and their judgment of the project parameters) and evaluate the progression of the capital costs and construction duration from the FOAK project to the NOAK project in the order book. Essentially, levers are the input parameters for the framework and are set by the user, and variables are intermediate parameters that are calculated using levers. Variables provide important insights into project performance and are therefore calculated and reported. Levers and variables together are used to calculate the costs in individual accounts and eventually the FOAK to NOAK capital costs. Levers, variables, and accounts are described in Sections 3.1.1, 3.1.2, and 3.1.3, respectively.

Another important aspect of the framework is the baseline cost. The baseline cost is the input cost estimate that the levers 'act' on to calculate the FOAK to NOAK cost estimates. The baseline cost is described in more detail in Section 3.2.

Perhaps the most important aspect of the framework are the relationships between the levers, variables, accounts and how they are used to adjust the baseline cost to calculate FOAK to NOAK costs. Most of the relationships are essentially simple equations (mostly linear statistical correlations) based on informed assumptions and rationale. These relationships and the associated equations, assumptions, and references are described in Section 3.3.

3.1.1 Levers

Levers are the main parameters that users can adjust to generate different cost reduction scenarios. Note that many levers are subjectively defined and should be chosen accordingly. The following levers are currently included in the framework:

- **Number of firm orders**: This determines the size of the order book for a given reactor concept. It directly impacts equipment costs for all plants within the order (including the first).
- **Include 1st plant in averages**: This lever allows the user to choose to ignore (FALSE) or include (TRUE) the impact of the first plant in the overall order book average (e.g. if investment in the first plant is already accounted for separately as is the case with ARDP).
- **Interest rate**: Represents the cost of borrowing money used to finance a project using debt. This is provided as a percentage. It should be inferred that this lever may account for any subsidized low-interest rate that a company may qualify for the clean energy investment (e.g., from the DOE Loan Program Office).
- **Investment tax credits (ITC) and the number of plants in the order book ITC is applied to**: Represents federal tax credits that can be claimed by the generation owner after project completion. While production tax credits (PTC) might also prove to be an invaluable mechanism for reducing levelized costs of electricity, only ITC is considered here since the study only focuses on capital expenses and does not account for operational ones. ITC is also applied to the first few plants of the order book as chosen by the user.
- **Design completion before construction start**: Percentage of design completed when construction of the plant begins. Historically, FOAK plants have started construction with an incomplete design. When construction begins with a lower design completion, there are typically more licensing amendments and rework, resulting in delays and cost increases. This lever has been identified as one of the most significant contributors to cost and schedule overruns (Buongiorno 2018).
- **Design maturity**: This indicate how many NPP designs currently being considered for deployment require new components that have never been built before and potentially result in supply chain delays. This novelty is represented by the design maturity lever. In the framework, this lever can be provided as one of three options: most components are new and therefore design maturity is low (value of 0), most components are deployed in the non-nuclear industry but never in nuclear and therefore design maturity is medium (value of 1), or most components have already been deployed in nuclear and therefore design maturity is high (value of 2).
- **Supply chain service proficiency**: This represents the proficiency of the supply chain. Proficiency could be interpreted as a combination of a contractor past experience and performance, as well as the methods or technologies used by the contractor to accomplish the tasks. A score between 0-2 (with decimal increments; 0 representing lowest proficiency and 2 representing highest) can be assigned for this lever by the user. Note that this study does not intend to judge the proficiency of these contractors and only intends to highlight the impact of this parameter on cost and schedule.
- **A/E proficiency**: This represents the proficiency of the architect/engineering (A/E) contractor. Similarly to above, a score between 0-2 (including decimal increments) can be assigned for this lever by the user.
- **Construction Proficiency**: This represents the proficiency of the construction contractor. Again, a score between 0-2 (including decimal increments) can be assigned for this lever by the user.

- **Number of plants to achieve best proficiency**: For each of the supply chain, A/E, and construction proficiency, the maximum proficiency can be assumed to be reached after a certain number of plants are deployed. A default value of 3, 4, and 5 plants, respectively, is assigned that can be adjusted by the user.
- **Cross-site standardization**: Represents the percentage of the design that is standardized between different sites. Typically, elements of the plant design (especially civil works, which constitute account 21 – Structures and Improvements) change due to site-dependent parameters such as topography and local natural hazards (earthquake, tsunami, etc.). Reducing these changes through technologies like seismic isolation will increase standardization between different sites.
- **Modular civil construction**: A 'TRUE/FALSE' toggle to represent if the construction leveraged modular methods such as steel composite (SC) walls.
- **Commercial BOP**: This lever determines if the balance-of-plant (BOP) can be commercially sourced from non-nuclear vendors (TRUE) or if it is safety-related and subject to nuclear qualifications (FALSE).
- **Non-safety-related reactor building (RB)**: This lever represents the safety-related classification of the RB. While the RB is typically safety related, advanced reactor technologies with superior passive safety features (e.g., TRISO-fueled reactors) can potentially make the case for not needing the RB for safety function (TRUE value). In this case, the RB can be classified as non-safety-related or non-safety-related with special treatment (NEI, 2019a), both of which have stringent requirements.

While the levers can be set for the first plant in an order book, and changed for all subsequent plants, it is important to highlight that an embedded logic is implemented to infer how they would evolve with a large order book. For example, while design maturity and supply chain proficiency may be low for the first plant, the framework implicitly assumes that this increases after subsequent plants are built. The logic followed in the framework to model this increase is described in Section 3.3.2. A key assumption here is that almost the same design (with limited standardization captured in the cross-site standardization lever) and same contractors (for A/E, construction, and supply chain) are leveraged with each subsequent plant, thereby maximizing the transfer of best practices and lessons learned. This also entails that the construction timeline of subsequent plants is assumed to be staggered in an optimal pattern such that there are minimal losses in experience and workforce between projects (in reality, there will likely be delays that lead to 'losses' in both know-how and workforce that it is not transferred from one plant to the next). These losses are not modeled in this framework and could be investigated in further work.

3.1.2 Variables

Variables are parameters that affect the cost but cannot be controlled directly - they are calculated using the levers listed above. However, the variables chosen in this study provide important insights into project performance are often used in the literature as indicators or quantities of interest to assess project performance. The following variables are included in the framework:

- Amount of rework: This variable represents the work that must be redone after initial completion due to design changes, quality control, or inspection failures. It is expressed as a percentage of the total plant that needs to be reworked.
- Supply chain delays: This variable represents the schedule delays incurred due to longer than planned lead times or other supply chain delays. This is expressed in months.
- Labor productivity: This variable represents the productivity of on-site labor in comparison with the baseline case. This is also expressed as a percentage.
- Bulk order reduction: This variable represents the cost reduction of factory-manufactured components in large volumes when there is a bulk order as a result of a firm order book. The assumption here is that with a firm order book, component vendors can offer reduced cost of components per unit since

they can distribute the up-front capital costs involved (e.g., for building or repurposing a factory) over a larger order size.

- Efficiency from experience: As more plants are built, efficiency in both labor allocation as well as material usage increases resulting in reduced labor and material costs. This is captured using the efficiency from experience variable.

3.1.3 Accounts

Only the capital cost accounts that typically constitute the largest parts of the total capital investment (TCI) are considered in this study, and only higher-level accounts are considered. Primarily, these costs include direct, indirect, and financing cost accounts. Together, these accounts make up most of the TCI and will also likely comprehensively capture the impact of all the levers and variables listed in the previous sections.

The accounts considered in the cost reduction framework are listed in Table 11 in Appendix B. Note that not all owners' costs are accounted for, and no contingency is assumed in the framework. Additional accounts can be added to the cost reduction framework, but the current version of the framework does not consider the cost evolution of these accounts (that is, the costs will remain the same from FOAK to NOAK projects regardless of the levers).

In addition to calculating the costs in these individual accounts, the following quantities that represent capital cost are also calculated:

- Overnight capital cost (OCC): OCC is calculated as the sum of all capital cost accounts except for financial costs. In this study, OCC is calculated by summing the costs of accounts 10 through 50.
- Total Capital Investment (TCI): TCI is calculated as the sum of all capital cost accounts including financial costs. TCI is calculated by summing the costs of account 10 through 60.
- Net OCC: Net OCC is the OCC adjusted with returns from ITC. Although ITC does not reduce costs, net OCC is assumed to represent the impact of ITC on overnight capital investment and is calculated and reported in this study.
- Net Capital Investment (NCI): NCI is the TCI adjusted with ITC, i.e., the sum of net OCC and financial cost. NCI is assumed to represent the effect of ITC on the capital investment of the project.

3.2 Reactor Concept Use Cases and Baseline Cost Estimate

Given the lack of real cost data for advanced reactors and the variability in the FOAK costs of these reactors, it is challenging to identify a starting point for estimating the FOAK to NOAK costs in this framework. In this study this challenge is addressed by using an estimate of a well-executed FOAK with a single plant in the order book (WE-FOAK) as the starting point or the baseline, and levers are applied to the WE-FOAK cost estimate to calculate the FOAK through NOAK costs. The WE-FOAK consists of a single, independent deployment of a plant, but without any unexpected overruns. The primary reason for using the WE-FOAK as a baseline is because it could be considered a 'clean slate'. It does not include the quantification of poor project execution or supply chain delays, nor the quantification of cost reduction benefits such as those from placing a bulk order for components or the experience gained from repeated deployments from FOAK to NOAK. It essentially represents a cost estimate with all the levers that cause overruns—design completion before construction starts, design maturity, A/E, supply chain, and construction proficiency—are all set to their best values, and all the levers that result in cost reduction—order book size, modular construction, non-safety-related RB, etc.—are set to their worst values. Note that care must be taken with the cost reduction levers that depend on plant design. If the plant design already includes one of these cost reduction techniques, it should not be included as a lever. For example, an advanced reactor plant design that already includes a non-safety-related RB, and the baseline cost estimate includes this, this lever should not be included in the calculation (i.e., set to one value and not changed). Therefore, the baseline cost estimate does not capture any learning or benefits from large ordering, nor does it account for reworks or delays that plague typical FOAK deployments. Essentially, the baseline cost was constructed to be entirely independent from the impact of the various levers. This allows the framework to manipulate and adjust these baseline costs based on the value selected for a given lever.

Two use cases were selected for this study, and the baseline costs were evaluated for each. The motivation for exploring pathways for a High Temperature Gas Reactor (HTGR) and Sodium Fast Reactor (SFR) example concepts stems from the reactor types being demonstrated under the DOE Advanced Reactor Demonstration Program (ARDP)[b]. However, the cases evaluated in this report do not represent the Xe-100 or Natrium projects. Although results are presented for these two cases, a comparison between them should not be interpreted as conclusive assessment of which design is more competitive, especially given the uncertainties involved in cost estimation. Descriptions of the cases are as follows:

- **Reactor Concept A**: This is a multi-unit plant with a relatively large total power output. Cost estimates developed for the Next Generation Nuclear Plant (NGNP) program were used as a an HTGR use case (Gandrik 2012). The NGNP program considered several plant layout variants. For the purposes of this study, the prismatic 264 MWe/unit with an outlet temperature of 750°C arranged in a 4-unit layout was selected.
- **Reactor Concept B**: This is single unit plant with a smaller output than Concept A. The Power Reactor Innovative Small Module (PRISM) concept was used as an SFR use case (Prosser 2023). Here as well, PRISM consisted of several design variants that were considered in the past. For the purposes of the current study, the 311 MWe/unit in a single-unit layout was considered. No thermal storage system is considered in the design.

The baseline cost estimates for Reactor Concepts A&B were calculated from a combination of sources and are presented in Table 1. The following subsections describe the calculation of the baseline costs.

Table 1. Baseline (well-executed FOAK) costs for the two use cases. All values are in 2022 USD.

		Reactor Concept A (4x264 MWe)	Reactor Concept B (1x311 MWe)
	Construction Duration (Months)	**125 months**	**80 months**
10	**Capitalized Preconstruction Costs**	**$ 162,925,273**	**$ 78,991,565**
11	Land and land rights	$ 15,000,000	$ 11,000,000
12	Site permits	$ N/A	$ 1,598,891
13	Plant licensing	$ 107,009,772	$ 24,382,988
14	Plant permits	$ 4,721,019	$ 12,679,167
15	Plant studies	$ N/A	$ 12,679,167
16	Plant reports	$ N/A	$ 3,972,186
18	Other preconstruction costs	$ 36,194,482	$ 12,679,167
20	**Capitalized Direct Costs**	**$ 4,600,597,497**	**$ 1,917,688,556**
21	Structures and improvements	$ 914,902,742	$ 244,678,343
22	Reactor system	$ 1,827,425,567	$ 911,334,797

---

[b] https://www.energy.gov/ne/articles/infographic-advanced-reactor-development

232.1	Energy conversion system	$ 584,352,743	$ 347,558,121
233	Ultimate heat sink	$ 89,555,306	$ 41,285,901
24	Electrical equipment	$ 140,508,400	$ 67,451,645
25	Initial fuel inventory	$ 451,686,471	$ 279,724,434
26	Miscellaneous equipment	$ 214,388,491	$ 25,655,316
30	**Capitalized Indirect Services Costs**	**$ 4,286,760,804**	**$ 811,425,471**
31	Factory and field indirect costs	$ 691,566,348	$ 146,077,241
32	Factory and const. supervision	$ 2,732,349,941	$ 505,665,054
33	Startup costs	$ 114,950,126	$ 21,273,359
34	Shipping and transportation costs	$ 9,678,929	$ 1,791,241
35	Engineering services	$ 738,215,460	$ 136,618,577
50	**Capitalized Supplementary Costs**	**$ 48,322,372**	**$ 14,866,323**
51	Taxes	$ 187,500	$ 187,500
52	Insurance	$ 39,993,112	$ 12,281,013
54	Decommissioning	$ 8,141,760	$ 2,397,810
60	**Capitalized Financial Costs**	**$ 4,259,911,398**	**$ 1,108,961,722**
62	Interest during construction	$ 4,259,911,398	$ 1,108,961,722
	OCC	**$ 9,098,605,946**	**$ 2,906,905,624**
	Normalized OCC ($/kWe)	**$ 8,616**	**$ 9,347**
	Total Capital Investment (TCI)	**$ 13,358,517,344**	**$ 4,015,867,345**

3.2.1 Capitalized Preconstruction Costs

The capitalized preconstruction costs were taken from Gandrik (2012) for the Concept A. For concept B data was leveraged from Prosser (2023) and TIMCAT analyses done in this work scope. Not all non-direct costs were available in Gandrik (2012). As a result, some costs that are relatively inconsequential were ignored while other missing indirect costs were included based on information from Prosser (2023).

3.2.2 Capitalized Direct Costs

The Nuclear Cost Estimation Tool (NCET) as part of the TIMCAT repository of tools was leveraged to estimate the capitalized direct costs (account 20) and the baseline construction duration. The TIMCAT repository of tools provides the capability of performing bottom-up cost estimation of NPPs[c] for both FOAK and NOAK projects. The ACCERT software developed by the SA&I program also offers a capability of performing bottom-up cost estimation but does not yet have the capability to estimate FOAK and NOAK costs. Since FOAK costs are specifically needed for the baseline estimate in this study, TIMCAT was used instead. The NGNP design and cost data were based on series of INL reports (Gandrik 2012). In a previous work, an NCET model based on this information was created and compared to the NGNP team's cost estimate, showing in general good agreement (within 10%) (Stewart 2021). Similarly, for PRISM, the recent Strategic Analysis and INL report on bottom-cost estimation, was leveraged to obtain data and build an NCET model (Prosser 2023). Figure 4 shows the comparison of the high-level code-of-accounts. The main difference is the percentage of cost for reactor equipment is significantly

---

[c] https://github.com/mit-crpg/TIMCAT

higher in NCET. Overall, the resulting total capital cost estimated in NECT (and used in this study) is 20% higher than the estimate in Prosser (2003).

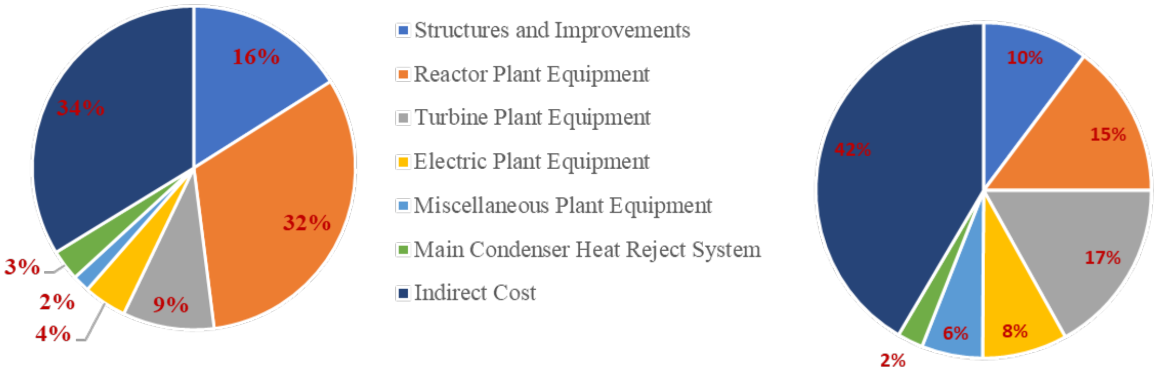


Figure 4. Comparison of NCET cost estimations in literature (left) vs. PRISM estimation (right).

3.2.3 Capitalized Indirect Services Costs

Most studies in the literature perform a top-down estimate of indirect costs, where the costs are scaled linearly with direct costs and/or construction duration. In a methodology developed by Stewart (2022b), the calculation of indirect costs within nuclear reactor construction projects is performed through the equation below. The equation delineates the relationship between indirect costs and direct costs, factoring in both primary and secondary effects that influence cost behavior. The equation is structured as follows:

$$Indirect\_cost_x = Direct\_cost_y \times F_x \times E_x \tag{1}$$

In this equation, Indirect_cost$_x$ represents the total indirect factory cost, indirect materials cost, or indirect labor cost. F is a scaling factor that identifies the primary correlation driving the cost, and E represents an escalation factor that accounts for secondary effects contributing to cost increases. Stewart (2022b) assumed that indirect labor costs to be mostly temporary construction facilities which likely scaled with the volume of site labor, indirect material costs to be mostly major construction equipment and tools purchases and maintenance which likely scaled with the volume of site material cost, and indirect factory costs to be mostly field supervision and quality assurance, so they likely scaled with the direct site labor costs (and not direct factory costs). They calculated these factors based on PWR12 BE and PWR12 ME data in EEDB. Table 2 shows the scaling parameters F and E in equation (1) as calculated by Stewart (2022b).

Table 2. Indirect cost scaling parameters calculated by Stewart (2022b).

	Direct_cost$_y$	F_x	E_x
Site labor cost	Direct_cost$_{labor}$	0.36	1
Site material cost	Direct_cost$_{material}$	0.785	$\frac{New\ plant\ average\ \#\ of\ workers}{PWR12BE\ average\ \#\ of\ workers}$
Factory equipment cost	Indirect_cost$_{labor}$	3.661	$\frac{New\ plant\ construction\ time}{PWR12BE\ construction\ time}$

An assumption here is that the PWR12-BE averages 12.1 million working hours across 72 months, equivalent to employing an average of 1,058 workers assuming 160 working hours per month. Therefore, the average number of workers for another plant (that is not PWR12BE) is derived using the equation:

$$New\ plant\ average\ \#\ of\ workers = \frac{Direct_{labor\ hours}}{construction\_months * 160} \tag{2}$$

In this study, the indirect material cost and indirect labor cost calculated by Stewart (2022b) are attributed to account 31, which covers factory and field indirect costs. Likewise, indirect factory costs are categorized under account 32, representing factory and construction supervision expenses.

Accounts 33 to 35 correspond to startup costs, shipping and transportation, and engineering services, respectively. For the Reactor Concept A, the costs are calculated by applying scaling factors to construction supervision (COA 32). These scaling factors are derived from empirical data from the calculation of a 311 MWe SFR (Prosser 2023). For concept B, these costs are taken directly from Prosser (2023).

Table 3. Indirect accounts 33 to 35 as a percentage of account 32, adopted from Prosser (2023).

33 – Indirect Startup Costs	4.2%
34 – Indirect Shipping and Transportation	0.4%
35 – Indirect Engineering Services	27.0%

3.2.4 Capitalized Supplementary Costs

To calculate capitalized supplementary costs, different methodologies were used depending on the account. All the methodologies for capitalized supplementary costs followed the approach detailed in Abou-Jaoude (2024). For account 51, taxes[d], the approach takes the average industrial property taxes for the largest cities in each state (1.25%) and multiplies it by the cost of land in account 11. For account 52, insurance[e], it is assumed that insurance is 0.45% of overnight capital costs (OCC). Finally, for account 54, decommissioning, it was assumed that the first payment into the decommissioning trust happened upon completion of the project at $10/kWe. Abou-Jaoude (2024) describes that this value is derived using industry data and calculating required annual payments to meet minimum fund requirements set out by the NRC.

3.2.5 Capitalized Financing Costs

To calculate capitalized financing costs, the cost of interest accrued during construction was calculated using a spend curve (i.e., capital spending vs. time during the construction duration) calculated using the TIMCAT scheduler, and an assumed interest rate, which is input by the user as a lever. For simplicity, the spend curves were calculated for the baseline case using the TIMCAT scheduler, normalized both in the X axis (duration normalized to the baseline duration) and the Y axis (spending normalized to the baseline OCC), and scaled for the other cases that have different OCCs and construction durations. In other words, the same ‘shape’ of spend curve is used for all cases of each reactor design. These normalized spend curves, calculated separately for each reactor design, are shown in Figure 5 below.

---

[d] This account represents specifically property taxes and no other forms of taxes.

[e] Insurance in this context is only insurance during construction

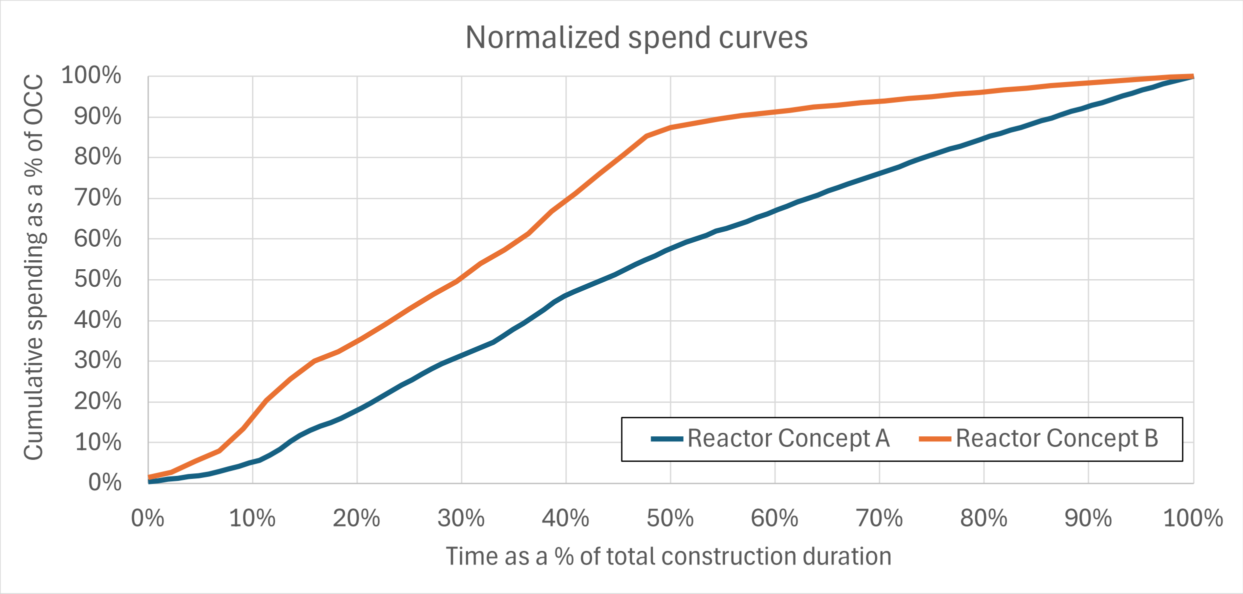


Figure 5. Normalized spend curves (X axis normalized to the baseline construction duration and Y axis normalized to the baseline OCC) for the two reactor concepts.

It should be noted that these spend curves do not include startup duration, which was determined separately from construction duration. It is assumed that cumulative spending reaches 100% before startup testing begins (which is a reasonable assumption since most spending occurs during the construction period) and during the startup testing duration the spending is almost negligible. The first plant is assumed to have a 16-month startup duration for both reactor concepts during which time, interest is accumulated without additional spending. After the first plant, a learning rate of 30% is applied to subsequent startup times as described in the next section (Section 3.2.6). Interest is therefore a function of the full duration (construction plus startup) as demonstrated in equation (3) below.

$$IDC = \sum_{t}^{T} \mathrm{OCC}(1 + Rate)^{t} - OCC \tag{3}$$

where,

IDC represents total interest accumulated during construction

t represents a given period

T represents the construction duration

β_t represents the portion of OCC spent in a given period t

$Rate$ represents the interest rate.

3.2.6 Construction Duration

Construction duration is an important aspect of capital cost estimation since it has a significant impact on indirect costs as well as financing costs as well as financing costs. In this study, with the NGNP and PRISM NCET models, the construction schedule was simulated based on over 200 tasks with dependencies and sequence as previously considered reactor designs (Stewart 2022a). This is implemented in a TIMCAT scheduler tool, which provides the monthly labor hours based on craft types over a certain construction period. The labor hours can then be used to inform onsite project spend rate beyond the engineering and equipment procurement that mostly takes place ahead of construction. The baseline was created assuming no cost overrun and fully modularized equipment installation but not modular building construction. Additionally, no firm order book was assumed here, no new standardization was assumed, and the build was therefore assumed to be perfectly executed (within the confines of a realistic FOAK). This resulted in a construction duration of 125 and 80 months respectively for Reactor Concept A&B (note that Concept A is a 4-unit arrangement). This construction duration does not include the time for start-up activities including fuel loading and testing, which were estimated separately as the ‘startup duration’. The baseline startup duration was assumed to be 16 months, same as the APR1400 plant construction in Barakah, UAE (World Nuclear News 2018).

3.3 Execution of the Framework

With the basic components of the cost reduction framework and the starting point of the calculation introduced, this section describes the execution of the framework. The basic order of steps involved in the execution are as follows. These steps are also illustrated in Figure 6.

1. Choose a baseline cost estimate that is (to the best extent) devoid of overruns and effects of learning and standardization. This can also be interpreted as a highly optimistic FOAK cost estimate.
2. Input levers described in Section 3.1.1.
3. Calculate FOAK cost.
    a) Calculate all variables using levers.
    b) Apply levers and variables to the baseline to calculate FOAK cost.
4. Calculate 2OAK cost to NOAK cost.
    a) For each “N” (2 for 2OAK, 3 for 3OAK, etc.), update levers and variables.
    b) Apply the updated levers and variables on the baseline to calculate 2OAK to NOAK cost.
5. Generate results.

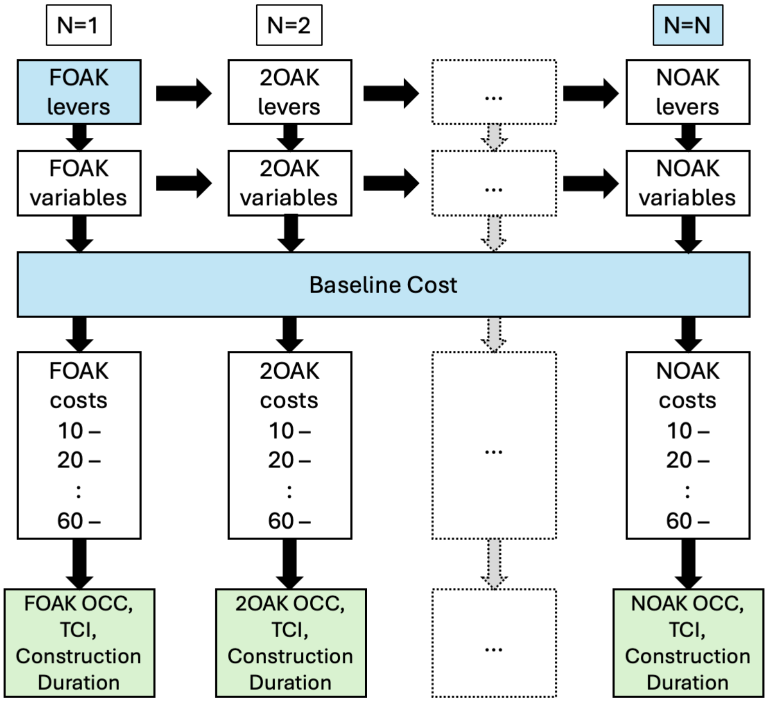


Figure 6. Evaluation of costs from the baseline to FOAK, 2OAK, and so on until NOAK. Inputs are in blue boxes and outputs are in green boxes.

The most important aspect of the execution of this framework is the relationships between different components. These relationships, indicated in the figure above by arrows, determine how the input levers are converted to variables, and how these variables and levers are applied to the baseline cost to calculate the FOAK to NOAK costs. In this study, these relationships are calculated through a combination of literature review, benchmarking with statistical observations and cost trends reported in the literature, and judgment. Almost all relationships are either based on simple proportionality or linear equations. All the relationships in the framework, underlying assumptions, and corresponding equations are described in this section. The subsections below describe two types of relationships: (1) between levers, variables, and accounts that enable execution of each column in Figure 6 and (2) updating levers from 1 to N and progression from FOAK to NOAK.

3.3.1 Relationships Between Levers, Variables, and Accounts

Figure 7 below presents a flowchart that shows the relationships between different levers, variables, and accounts. As seen in the figure, cost accounts are affected by either variables or levers, and the variables themselves are affected by levers. Changing the levers, therefore, will change the variables as well as the costs for each calculation from FOAK and NOAK. These relationships and their corresponding rationale are described in Table 4 (relationships between levers and accounts), Table 5 (relationships between levers and variables), and

Table 6 (relationships between variables and accounts). Additional justification on all the various correlations used is provided in the Appendix sections.

The following is a list of notations used in the tables and what they represent:

- $Cost_T^a$ = Total costs for a given account a
- $Cost_f^a$ = Factory costs for a given account a
- $Cost_m^a$ = Material costs for a given account a
- $Cost_l^a$ = Labor costs for a given account a

The total cost of an account is then calculated as follows:

$$Cost_T^a = Cost_f^a + Cost_m^a + Cost_l^a \tag{4}$$

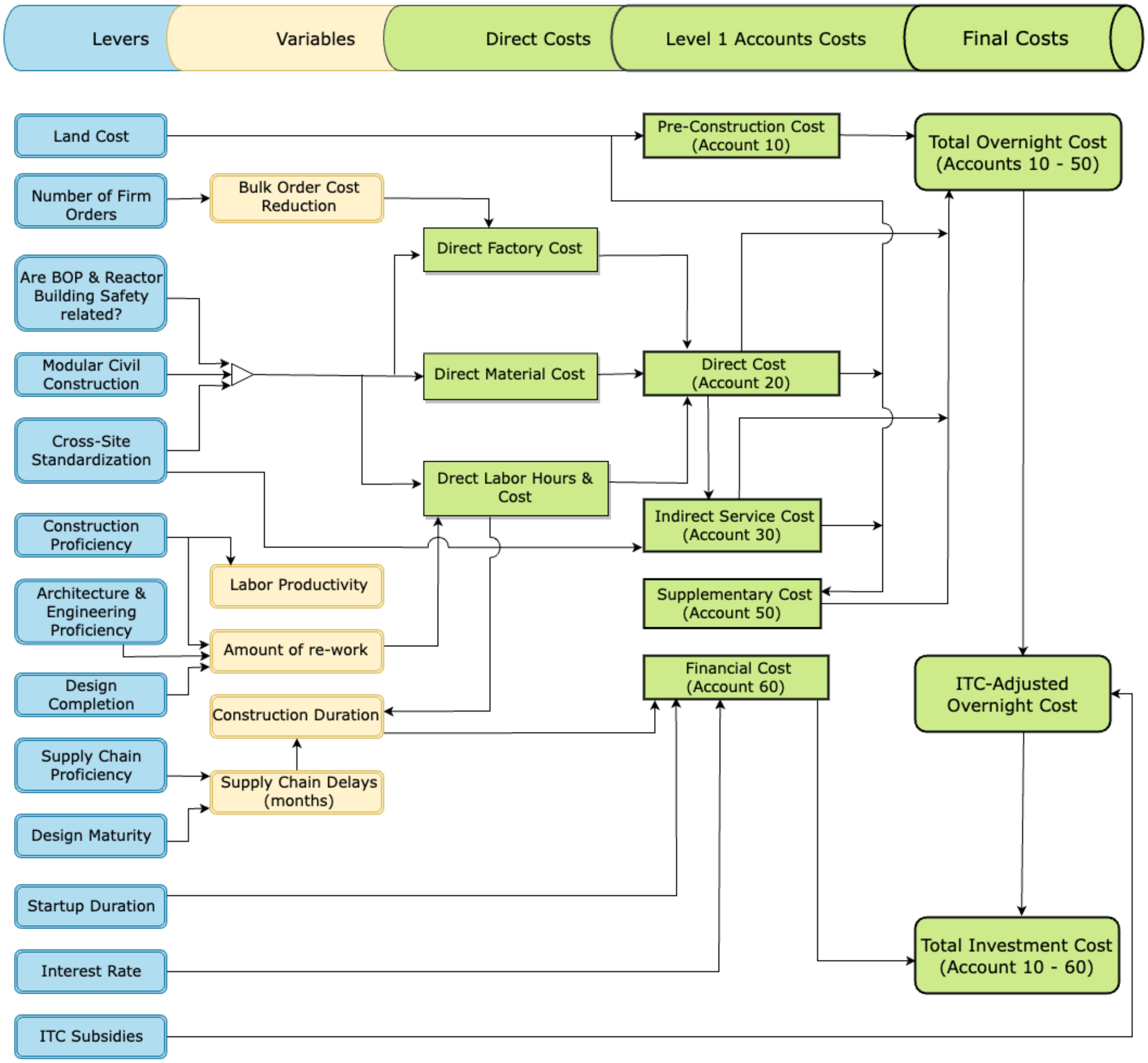


Figure 7. An illustration of the relationships between levers, variables, and accounts in the cost reduction framework.

Table 4. Relationships between levers and variables, and the associated justification

Lever	Variable	Relationship and Justification
Design completion, DC (%)	Rework, RW (%)	$RW = -0.69 * DC + 0.69$ (Concept A) $RW = -0.9 * DC + 0.9$ (Concept B) Justification: See Section A.1.3.
Design maturity, DM, and supply chain service proficiency, PSP	Supply chain delay, SCD (months)	$SCD = -6.0 * DM - 3.0 * PSP + 18.0$ (both concept) Justification: See Section A.2.

Lever	Variable	Relationship and Justification
A/E proficiency, AEP	Rework, RW	$RW = -0.13 * AEP + 0.25$ (Concept A) $RW = -0.15 * AEP + 0.30$ (Concept B) Justification: See Section A.1.1.
Construction proficiency, CP	Rework, RW	$RW = -0.13 * CP + 0.25$ (Concept A) $RW = -0.15 * CP + 0.30$ (Concept B) Justification: See Section A.1.1.
Construction proficiency, CP	Labor productivity, LP	$RW = -0.15 * CP + 0.71$ (both concepts) Justification: See Section A.1.2.
Cross-site standardization	Efficiencies from experience, EXP	$EXP = \frac{CSS}{CSS_{base}}$ (both concepts) Justification: It is assumed that the efficiency from experience increases with standardization increase from the baseline. This is because as standardization increases and similar tasks are performed at the site, labor and material efficiencies will increase.
Number of firm orders, N	Bulk order reduction, BOR	To calculate bulk order reduction for factory-manufactured components, it is first assumed that when there is a bulk order for a component, the component vendor will provide a bulk order discount and the component cost charged by the corresponding vendor for all plants from FOAK to NOAK will be the same. If the vendor receives a bulk order of size N, the following assumptions are made to roughly estimate this discount as well as the cost of the components to the buyer: • The marginal cost of manufacturing the component for the vendor follows the learning rate equation, with the FOAK component marginal cost being the same as the baseline cost. • An exponential volume production curve is fitted into the ratio of NOAK to FOAK factory equipment costs calculated using TIMCAT for each reactor concept to calculate a bulk ordering equation for each factory-manufactured account. • Using these bulk order unit costs, the marginal production cost to the vendor is calculated from FOAK to NOAK components. • BOR is calculated as the ratio of the average cost of FOAK to NOAK components to the cost of the FOAK component. • The cost to the buyer is then estimated as the average of marginal production costs from FOAK to NOAK component added to the capital cost of the initial investment in a factory equally distributed over N orders. Given this assumption, the vendor charges the same cost for both the FOAK and NOAK plants. • Using these assumptions, the following equation is used to estimate the BOR.

Lever	Variable	Relationship and Justification
		$BOR = \frac{\sum_{i=1}^{N} C_1 * (1 - LR)^{log_2 N}}{C_1 * N} = \frac{\sum_{i=1}^{N} (1 - LR)^{log_2 N}}{N}$

Table 5. Relationship between levers and accounts and the associated justification (all relationships are the same for both reactor concepts considered here).

Lever	Account	Relationship and Justification
Modular civil construction	21 – Structures and Improvements	If lever is TRUE, construction duration is reduced by 20% for both reactor concepts. Justification: This is based on the studies documented in Stewart et al 2022a where the impact of modularity on the cost and schedule is comprehensively investigated. It is also assumed that modularity does not impact direct cost, based on the same study.
Non-safety-related reactor building, NSR-RB	212 – Reactor Containment Building	If lever is TRUE, $Cost_{T,updated}^{212} = Cost_{T}^{212}(1 - 0.4).$ If lever is FALSE, there is no effect since the baseline case assumes that the RB is safety related Justification: There is no publicly available cost data that can be used to correlate capital costs for different safety classifications. However, nuclear cost premiums (increase in costs from a non-nuclear application to a nuclear application described a cost multiplier) for labor and material have been documented in by Delene (1993) as from 1.1 to almost 5, depending on the type of material and labor skill. For simplicity, it is assumed that making the RB non-safety-related reduces the total direct cost of the RB by about 40%. This corresponds to a nuclear premium of 1.67.
Commercial BOP, C-BOP	213 – Turbine Building and Heater Bay 232.1 – Energy Conversion System	If lever is TRUE, $Cost_{T,updated}^{213,232.1} = Cost_{T}^{213,232.1}(1 - 0.4)$ If lever is FALSE, there is no effect since the baseline case assumes that the BOP is not commercial and is licensed by NRC. Justification: The same nuclear cost premiums documented by Delene (1993) used in the previous lever are used here. For simplicity, it is also assumed here that making the BOP a commercial project reduces the total direct cost of the BOP by about 40%. This corresponds to a nuclear premium of 1.67.
Cross-site standardization, CSS	35 – Engineering Services Cost	$Cost_{T,updated}^{35} = \left(\frac{1}{CSS_{base} - 1} * CSS - \frac{1}{CSS_{base} - 1}\right) * Cost_{T}^{35}$ where CSS_{std} is the baseline standardization (i.e., for the baseline case). Justification: The rationale here is that as more standardization is introduced in the baseline case, the engineering services costs should reduce as fewer things need to be redesigned. As standardization approaches 100% (or 1.0), engineering services

Lever	Account	Relationship and Justification
		costs are assumed to linearly decrease to zero. Therefore, a linear relationship is assumed between these two points to develop the equation above: $(CSS_{base}, 1.0)\ and\ (1.0, 0.0)$. CSS_{base} is assumed to be 70% in this study.

Table 6. Relationships between variables and accounts and the associated justification (all relationships are the same for both reactor concepts considered here).

Variable	Accounts	Relationship and Justification
Rework, RW	20s – Capitalized Direct Costs	This relationship assumes that rework involves redoing tasks that have already begun or finished. Therefore, rework will increase all the direct costs: factory, equipment, and labor. Accordingly, the following relationship is assumed: $Cost_{T,updated}^{20s} = (Cost_f^{20s} + Cost_m^{20s} + Cost_l^{20s})(1 + RW) = Cost_T^{20s}(1 + RW).$ In addition to the direct costs, direct labor hours are also increased accordingly for all accounts in the 20s: $Lab_{updated}^{20s} = Lab^{20s} * (1 + RW).$ Note that this variable is not applied to the initial fuel load (account 25).
Labor productivity, LP	20s – Capitalized Direct Costs	This relationship assumes that labor productivity will scale the labor hours for each account according to the following equation: $Lab_{updated}^{20s} = Lab^{20s} * \frac{1}{LP}.$ Therefore, productivity lower than 100% will increase the labor hours from the base case and vice versa. The direct labor hours will therefore also change similarly: $Cost_{l,updated}^{20s} = Cost_l^{20s} * \frac{1}{LP}.$ Other direct costs and initial core load costs (account 25) are not impacted by LP.
Supply chain delays, SCD	20s – Capitalized Direct Costs	Supply chain delays are not assumed to increase direct costs, but they do increase the construction duration. The impact of supply chain delays on the construction duration is described in A.2.
Bulk order reduction, BOR	20s – Capitalized Direct Costs	Cost of components manufactured in factories is reduced using BOR. Only the reactor equipment (account 22) and turbomachinery (account 232.1) are assumed to be modularized and factory fabricated. These costs are calculated as follows for all plants from FOAK to NOAK. $Cost_f^{22,232.1} = \frac{FactoryCost^{22,232.1}}{N} + FOAK\_Cost_f^{22,232.1} * BOR$

Variable	Accounts	Relationship and Justification
		Here, FOAK_Cost is the FOAK component cost, which is the direct factory cost for account 23 or 232.1. $FactoryCost$ is the initial capital to build a new factory or repurpose an existing factory. Since estimates of factory cost are not easily available in the literature, a cost of \$250 million is assumed for reactor components and \$150 million for turbomachinery. This is based on the following numbers: (a) anecdotal evidence that factory costs for building SC walls for Vogtle were around \$400 million, (b) the cost of a hypothetical factory producing a commercial version of the MARVEL microreactor was estimated to be around \$170 million by a recent study (Abou-Jaoude 2023), and (c) a recent announcement by Ultra Safe Nuclear Corporation that a factory for producing their microreactors was estimated to cost \$232 million[f].
Efficiencies from experience, EXP	20s – Capitalized Direct Costs	Efficiencies from experience are assumed to decrease the onsite direct labor and material costs for all accounts (except initial fuel core, account 25). This decrease is captured using the learning rate equation: $$NOAK\_Cost_l^{20s} = FOAK_{Cost_l}^{20s}(1-LR)^{\log_2 N}$$ $$NOAK\_Cost_m^{20s} = FOAK_{Cost_m}^{20s}(1-LR)^{\log_2 N}$$ where the subscripts l and m denote labor and material costs, respectively. While the FOAK costs are calculated using the baseline costs (and applying variables and levers), the subsequent plant (2OAK, 3OAK, and so on until NOAK) costs are calculated using this equation. The learning rate here is calculated separately for each account using the FOAK and NOAK costs of the baseline case calculated using TIMCAT. Note that TIMCAT performs a bottom-up estimation of the NOAK cost by applying account-specific learning rates. Using these FOAK and NOAK costs, the learning rates for each account in the 20s (for labor and material costs) were back calculated by fitting the learning rate equation and assuming that the NOAK costs were achieved after 10 plants. The assumption of 10 plants is also consistent with past recommendations on the number of plants it takes to reach NOAK costs (Buongiorno 2018 and GIF 2007).

Table 7: Ranges and description of each lever of the framework

Lever	Range	Description
Interest rate	0% - 20%	A representative interest rate to calculate the cost of debt.

---

[f] https://www.al.com/business/2023/06/gadsden-chosen-for-232-million-microreactor-assembly-plant-creating-250-jobs.html#:~:text=Seattle%2Dbased%20Ultra%20Safe%20Nuclear,the%20facility%20operational%20by%202027.

Lever	Range	Description
ITC and number of plants in the order book that may avail ITC	0% - 50%	Percentage ITC the project may qualify for.
Design completion before construction start	40% - 100%	While design completion as low as 30% is documented in Marciulescu (2019), a minimum design completion of 40% is assumed in this study.
Design maturity	0, 1, or 2	- 0 implies that most components of the design are novel and have never been deployed and therefore the project has low design maturity - 1 implies that most components of the design have never been deployed in nuclear, but they have been deployed commercially and therefore, the project has medium design maturity - 2 implies that most components of the design have been deployed in nuclear and therefore, the project has high design maturity.
A/E proficiency	0 to 2	A scale of 0 to 2 with 0 being low proficiency and 2 being high proficiency. Proficiency should be assigned based on the user's judgment of the contractor's proficiency and quality of performance in the past.
Construction service proficiency	0 to 2	A scale of 0 to 2 with 0 being low proficiency and 2 being high proficiency. Proficiency should be assigned based on the user's judgment of the contractor's proficiency and quality of performance in the past.
Supply chain service proficiency	0 to 2	A scale of 0 to 2 with 0 being low proficiency and 2 being high proficiency. Proficiency should be assigned based on the user's judgment of the contractor's proficiency and quality of performance in the past.
Cross-Site Standardization	0% - 100%	100% standardization indicates that plants across sites are identical. It is assumed that typically plant standardization is around 70%, so a value larger than that is recommended, unless there is a compelling reason.
Modular construction	TRUE/FALSE	Set to TRUE is modular techniques are used for buildings, and FALSE otherwise.
Commercial BOP	TRUE/FALSE	Set to TRUE if a commercial grade BOP (not licensed by NRC) is used and FALSE otherwise.
Non-safety-related RB	TRUE/FALSE	Set to TRUE if a non-safety-related classification is used for RB and FALSE otherwise.

Once the relationships in these tables are used to calculate the cost accounts and the total OCC and TCI, ITC is now applied. ITC is the only type of government support considered in this study. Previous work has been done to quantify the impacts of the Inflation Reduction Act (IRA) on O&M and construction costs. A report by Guaita (2023) was used to determine the impact of IRA ITC on construction costs. The report specifically provides a list of multipliers that can be used to adjust OCC for given ITC levels as shown in Table 8. These multipliers were used to represent the impacts of IRA ITCs on the costs of nuclear construction projects. It is vital to note that tax credits do not reduce the amount of costs incurred, they simply provide a new source of revenue upon completion of the project. For example, PTCs provide generators with annual cash inflows in the form of reduced taxable income or actual revenues (this is somewhat dependent on the entities tax status and monetization strategy). The ITC can be claimed all at once after operations begin or over multiple years. Again, this comes in the form of reduced taxable income or actual revenues. This is important because developers will still need to pay the full cost of the reactor. Tax credits do not change how much vendors will charge. In the context of this report, the cash inflows from the ITC are represented by decreasing the reported costs of the reactor to contextualize the impact. These decreases are reported in terms of net OCC and NCI defined in Section 3.1.3.

Table 8. Investment tax credit OCC multipliers from Guaita (2023).

Investment Tax Credit Level	OCC Multiplier
6%	.95
30%	.73
40%	.63
50%	.53

3.3.2 Progression from FOAK to NOAK

Once the FOAK costs are calculated using the levers and variables input by the user, the costs of subsequent plants in the order book are calculated. This is done by updating the levers (and consequently the variables and accounts) for the subsequent plants as follows:

- Interest rate: Interest rate can vary significantly over the time span it takes to build all plants in an order book. Given the complexities and the highly uncertain market forces that affect the interest rates, it is assumed that for simplicity, the rates are the same for all plants in the order book.
- ITC: ITC is applied to the first N_{ITC} plants as input by the user. ITC is assumed to remain the same for all these plants.
- Design completion before construction start: The user provided design completion percentage is set for the FOAK plant, but for the subsequent plants, a design completion of 100% is assumed.
- Design maturity: Regardless of the input for the first plant, the subsequent plants are always assumed to have full design maturity (lever is set to 2.0). The assumption here is that building the first plant sets up the necessary supply chains and the design is mature enough to not cause any supply chain delays.
- Supply chain service proficiency: If this lever starts with the least proficiency (lever is set to 0), it is assumed to take 3 plants reach full proficiency of 2.0, and the proficiency is assumed to increase linearly. Accordingly, if the FOAK plant starts with a higher proficiency, full proficiency can be reached faster.

- A/E proficiency: If this lever starts with the least proficiency (lever is set to 0), it is assumed to take 4 plants reach full proficiency of 2.0, and the proficiency is assumed to increase linearly. Accordingly, if the FOAK plant starts with a higher proficiency, full proficiency can be reached faster.
- Construction proficiency: If this lever starts with the least proficiency (lever is set to 0), it is assumed to take 5 plants to reach full proficiency of 2.0, and the proficiency is assumed to increase linearly. Accordingly, if the FOAK plant starts with a higher proficiency, full proficiency can be reached faster.
- Cross-site standardization: Standardization for the FOAK plant is always assumed to be 70%. If users input a higher standardization, this is applied in the calculations of the second plant onwards. The same standardization is assumed for all the subsequent plants.
- Modular civil construction: This lever can be set for the first or second plants. If either of them is set to TRUE, the subsequent plants will also be set to TRUE and construction duration reduction due to modular construction will be modeled for these plants.
- Commercial BOP: It is assumed that the design is updated to include a commercial BOP in either the FOAK plant or the second plant, and the design stays the same for the subsequent plants. Accordingly, the user can set this lever to TRUE or FALSE for the first or second plant and the same value will be used for the subsequent plants.
- Non-safety-related RB: Similar to commercial BOP, it is assumed that the design is updated to include a non-safety-related RB in either the FOAK plant or the second plant, and the design stays the same for the subsequent plants. Accordingly, the user can set this lever to TRUE or FALSE for the first or second plant and the same value will be set for the subsequent plants.

As described in Section 3.1.1, levers can be grouped into cost overrun levers and cost reduction levers. Given the assumptions and relationships listed above, all the cost overrun levers improve gradually and plateau at their ‘best’ values by the 5th plant at the latest. The construction proficiency is assumed to improve at the slowest pace and takes 5 plants to reach a proficiency of 2 the FOAK plant has a proficiency of 0. Additionally, the same EPC contractors are assumed to build all plants in a given order book. As more plants are built from FOAK to NOAK, reductions also result from experience-based efficiency, which increases labor and material efficiency and reduces the corresponding capital costs. Experience-based efficiency is also increase with the percentage of cross-site standardization and therefore, a higher standardization percentage will accelerate the cost reduction even after overruns are completely mitigated.

3.4 Limitations of the Framework

This study is based on a number of simplifying assumptions, many of which are based on past cost studies. While the report strove to focus on objective cost correlations from the literature, some should be recognized to be case-dependent but still represented the best available data readily available. Throughout the report, these assumptions are documented, and corresponding references are provided where applicable. These assumptions lead to various limitations (some that may have been stated previously in the text) which are summarized here. Further work could make the necessary improvements to address these limitations.

1. The capital cost estimates generated by this framework should not be taken as production level estimates. Professional cost estimators should be used to make cost estimates for specific projects. In fact, a professional estimate of an FOAK could be used to re-baseline this framework. This would allow users to then re-evaluate the impact of levers for their specific use case. At that stage, the framework could simulate the impact of changes in project execution (e.g., the user’s interpretation of construction contractor proficiency) and how repeated execution of the project will evolve capital costs from FOAK to NOAK.

2. Although the framework estimates construction duration in addition to the capital costs, this calculation is relatively simplistic. It only considers the impact of labor hours on the construction duration (i.e., a 50% increase in labor hours leads to a corresponding 50% increase in construction duration). The framework does not have enough granularity to identify which tasks are on the critical path and how task prioritization shifts. Labor allocation can significantly impact construction duration. The influence of levers such as modular construction (due to the significant reduction in on-site labor) and commercial BOP (due to a lack of NRC involvement) is for instance, not fully captured in the model. In reality, project managers can better optimize labor allocation on the construction site to reduce construction duration (Stewart et al, 2022a). Some of these effects are not entirely captured in the framework and could be incorporated in further work. A consequence of this limitation is that the impact of cost reduction levers such as modular construction are underestimated since their effect on schedule is not comprehensively captured.
3. The framework does not fully capture variations in decision making and factory investments as a function of order book size. For example, a component vendor may not invest large capital in factories if only small order book is secured, instead opting for more custom-built pieces which would change the assumption in this framework. Overall, the framework inherently assumes that there are sufficient orders to warrant an investment in a factory to produce reactor equipment. Additionally, the framework simplistically assumes a fixed equipment price throughout an order book, as described in Table 4. In reality, it is likely that a supplier may charge slightly more for the first orders but may end up reducing costs later on as experience is accrued in the manufacturing process and improvements in the factory implemented.
4. The choice of many levers, especially proficiency of EPC contractors, is subjective and based on the judgment of the user. This implementation is intentional because assigning proficiency to a contractor or a company can be relatively complex and is out of the scope of this study. Other subjective levers such as amount of design completion before starting construction and standardization can be estimated more readily if enough information on the project is available.
5. The calculation of financing costs assumes 100% debt ratio (i.e., 100% of the capital investment is debt), but a part of the investment could be equity. Further work could consider the incorporation of a debt ratio lever to allow stakeholders to better reflect the specific project financing strategy.
6. The levers and relationships all have significant uncertainties. These uncertainties can only be captured through a comprehensive uncertainty quantification analysis, which could also be performed as a part of further work.

4. COST REDUCTION PATHWAYS

With the cost reduction framework set up, the study can proceed to quantify possible pathways to reach competitive costs for nuclear energy. This section will provide a deep dive into a specific scenario to better illustrate how the framework can be employed. A comparison of four scenarios is then conducted, followed by a sensitivity analysis to identify important cost drivers. It is important to re-emphasize here that the quantitative estimation shown in this section should not be taken to be detailed projection of future cost. Rather they should be interpreted as a ‘best estimate’ that aggregates data and insights from the existing literature along with all the associated limitations of these studies. Additionally, while a range between 1-20 orders are considered in this report, to achieve the 200 GW of nuclear energy expansion by 2050 (DOE 2023, Abou-Jaoude 2024), substantially larger amounts of reactors would need to be deployed. Therefore, the results of this study should not be used to assess the long-term outlook for nuclear energy but should only be seen as a relatively short-term outlook for the first 5-20 plants if ordered together (again, readers are referred to Abou-Jaoude 2024 for longer term projections).

4.1 Deep Dive into a Single Scenario

To illustrate the capability of the framework and its flexibility, a deep dive into a single example is shown here. It will be referred to as Scenario 1 later in the discussion. Note that it is a slight modification of the scenario presented in the executive summary (it is assumed that none of the plants claim ITC in this scenario whereas the first plant is assumed to claim ITC in the modified scenario of the executive summary). The levers shown in Table 9 were selected for this case. It is assumed that an up-front bulk order of 13 plants was established prior to starting construction of the first reactor. The framework was setup to encourage the evaluation of benefits forming consortium with bulk orders up front to drive down costs (a single-plant order would constitute a lever value of N=1). The design maturity and construction proficiency of the leveraged firms was medium (= 1.0). The supply chain and architecture/engineering proficiency was set to low (= 0.5). The BOP was deemed commercial grade; hence, non-nuclear components could be leveraged here. Last, no government support is provided for this scenario (ITC set to 0%).

Table 9. Levers selected for Scenario 1.

Number of Firm Orders	13
Design Completion	80%
Design Maturity (0, 1, 2)	1
Supply Chain Proficiency (0-2)	0.5
A/E Proficiency (0-2)	0.5
Construction Proficiency (0-2)	1
Cross-Site Standardization	80%
Modular Civil Construction	TRUE
Commercial-grade BOP	TRUE
Non-safety-related RB	FALSE
ITC Amount	0%[1]

[1] In reality, it is likely that an ITC will be applied for the first plant. This is a hypothetical scenario that provides a starting point to this discussion

A detailed breakdown of the resulting timeline and costs based on the selected levers is provided in Appendix B (Table 12 and Table 13). The first step in the framework workflow was to calculate the construction duration for each of the 13 plants based on the levers. The results for both reactor types are shown in Figure 8. It can be seen how the timeline drops rapidly from the first reactor built (even higher than the baseline value since overruns and delays are now being accounted for) then appears to bottom out after ~4 plants. The model currently projects an approximate optimum of how much time reduction can be realistically achieved. It is important to highlight again here that while the construction duration for Reactor Concept A appears to be larger than for Concept B, the total power produced from Concept A in these use-cases is notably larger.

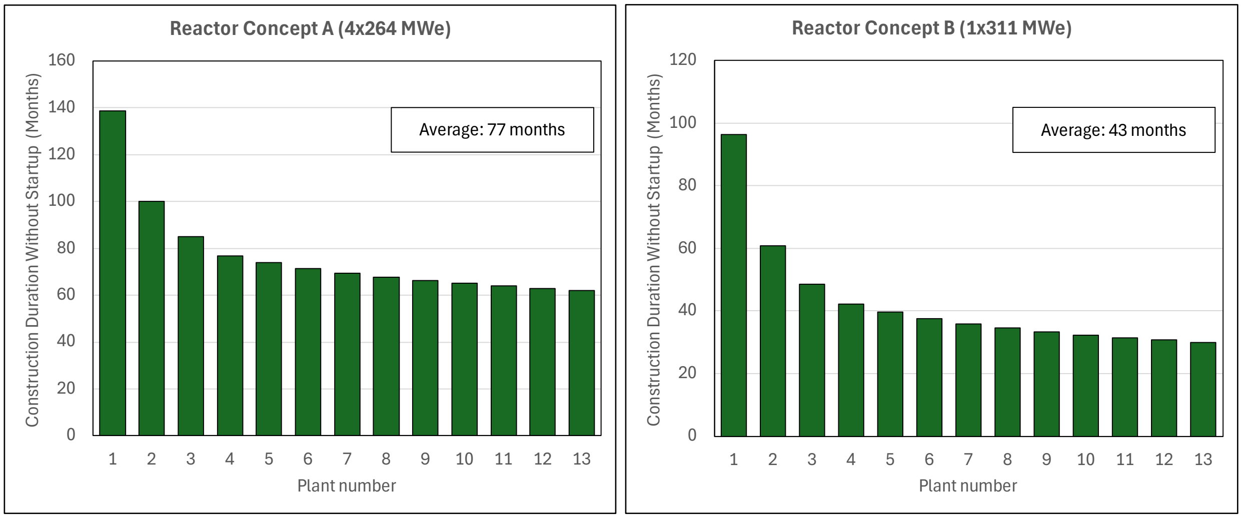


Figure 8. Evolution of the construction duration (without startup activities) for Reactor Concept A (left) and Reactor Concept B (right) based on the levers selected.

Based on the construction duration for each plant, the overall timeline for deployment of the order book of Reactor Concept A in a sequential manner is shown in Figure 9. It is entirely possible that several more reactors can be deployed within that timeline if they are constructed in parallel to the ones shown. However, parallel builds may not benefit as much from experiences gained from previous plants, as a staggered approach does. Therefore, to achieve maximum cost reduction, the model assumes all plants are sequentially built with 75% overlap. In other words, when 25% of construction is completed for plant N, construction for plant N+1 begins. This ensures a minimal amount of time lost between completing a given task and incorporating the lessons learned to the next plant. Based on these assumptions, it would take around ~13 years to realize the costs of the third plant (i.e., the cumulative cost reduction from FOAK), ~14 years to realize the costs the of the fourth plant, etc.

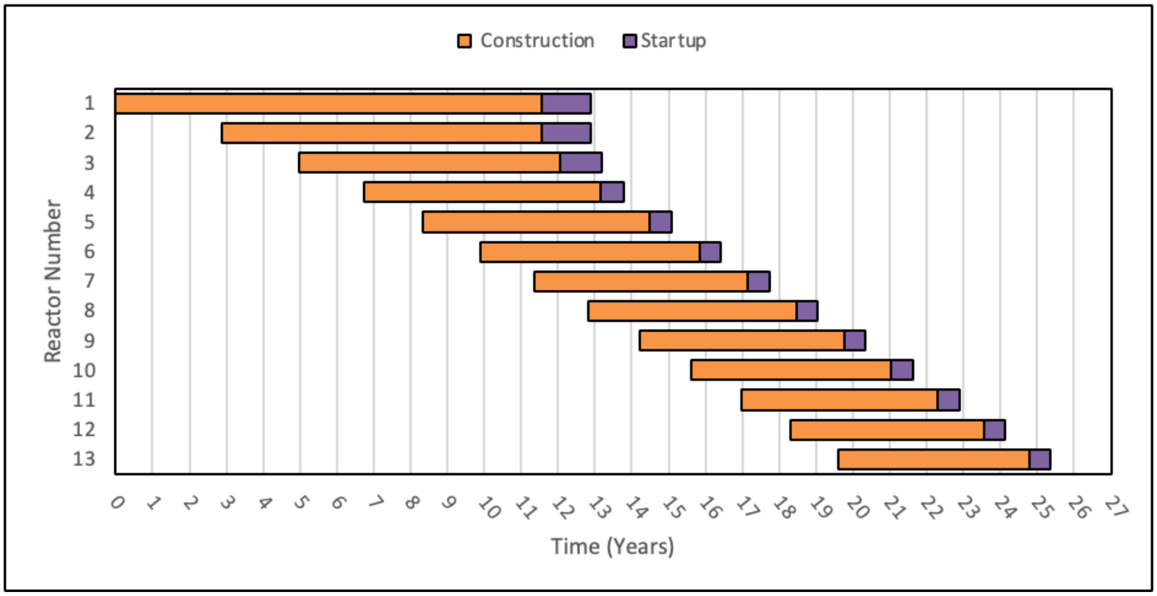


Figure 9. Sequential timeline of plants built in the order book in a staggered manner (assuming 75% overlap) for Reactor Concept A.

The resulting cost evolutions for the two reactor concepts cases are shown in Figure 10. The overall trend appears to somewhat mimic that of the construction duration in Figure 8, with the first several plants seeing very elevated costs that tend to reach a lower bound after 4–5 plants. This is mainly because the levers that cause overruns—design completion before construction start, design maturity, supply chain service proficiency, construction proficiency, and A/E proficiency—all attain their optimal values in about four plants (per the assumptions described in Section 3.3.2), subsequently eliminating any and all overruns experienced in previously.

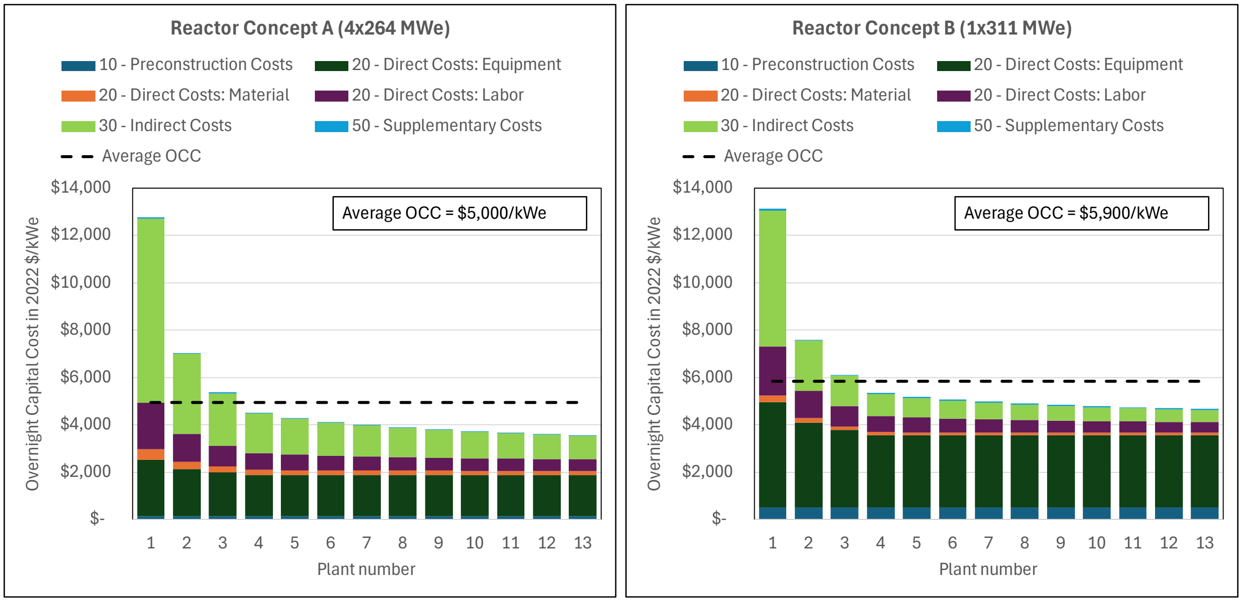


Figure 10. Normalized OCC for the Reactor Concept A (left) and Reactor Concept B (right) case under the levers selected in Scenario 1. Results should not be used to contrast the two reactor types, as discussed in the text.

Even though the levers for both concepts are identical, the average OCC across 13 plants for concept B is higher than for concept A. The differences can primarily be attributed to economies of scale – a single plant for reactor concept A has a total power output that is over 3x larger than reactor concept B (1056 MWe vs. 311 MWe), leading to lower normalized costs per kWe. Additionally, construction durations normalized to the power output vary substantially between the two designs – the normalized construction duration (averaged across the order book for this scenario) for concept A is about 73 months/GW and for concept B is about 138 months/GW. This again is due to better economies of scale for concept A. Normalized construction duration directly impacts the indirect cost as well as the financing cost (which will be reflected in larger normalized TCI values for concept B as shown in Figure 11). It is important to note that the occurrence of economies of scale in reality is subject to debate in the literature (e.g., Carelli 2010). Indeed, some research has argued that while larger designs may benefit from economies of scale, they run higher risks for overruns in general (Stewart 2022c). This can be seen in the results presented in Figure 10 as the normalized OCC of the first plant, which includes overruns, is almost identical for the two reactor concepts (concept A is only ~3% cheaper) and economies of scale are essentially dwarfed by cost overruns etc. As more plants of the same kind are built and overruns are mitigated, economies of scale become more apparent: the 13th plant of concept A is ~30% cheaper in terms of normalized OCC.

Some of the differences between the results are also due to the differences in the reactor concepts chosen as the two baselines. For example, the impact of many levers is dependent on the ratio of on-site versus off-site activities, which will be different for the two reactor concepts. In the scenario described here, on-site costs for the first plants of concepts A and B are 50% and 32%, respectively, of the corresponding total direct costs. The 13th plants of concepts A and B incur on-site costs of 35% and 16%, respectively, of the corresponding total direct costs. Full breakdown of the costs for the 1st, 2nd, and 13th plants in this scenario are provided in Table 12 and Table 13 in Appendix B for concepts A and B, respectively. In other words, concept A has more activities conducted at the site than at the factory, specifically, 1.5 – 2 times higher. While on-site activities (and factory activities) drop similarly for both concepts, the fact that their proportion of the total costs are different under each results in divergences as more units are built. Under the assumptions of the model, on-site activities undergo a larger reduction in costs than factory activities primarily because the benefits of equipment modularity (and not civil construction modularity) and factory production on cost are already accounted for in all plants starting from the baseline plant as described in Section 3.2.6 (hence more limited cost reduction for factory-based costs are observed between the first and last unit). Equipment modularity, although widely suggested as a way to reduce costs (Maronati, 2018), was not added as a lever in this study. Instead, it is assumed that all plants have modularized, factory-produced equipment since this is an attribute of most commercial designs currently under development starting from their first plant.

In addition to the ratio of on-site to off-site activities, there are other concept-specific features that affect the evolution of costs from FOAK to NOAK. It is important to emphasize that this study does not intend to quantify these effects conclusively or compare the economic competitiveness of the different reactor technologies or plants being pursued by the industry. This is more appropriately addressed by tools such as ACCERT (Zhou 2023, Bolisetti 2023). Instead, it only shows that the variations in plant designs (even within the same reactor technology) can lead to changes in how the cost evolves from FOAK to NOAK. It should also be noted that comparison of reactor types also extends beyond capital cost. For instance, the economic benefits of having a higher outlet temperature for an HTGR-type concept may be difficult to capture from a capital cost analysis alone. Similarly, the ability of an SFR-based concept to recycle fuel or achieve very high burnup levels can be difficult to quantify from a purely economic standpoint.

The next step in the framework calculation workflow is to account for the impact of interest accrued during construction. The resulting costs are shown in Figure 11. Here, the TCI value (including financing costs) is used as a reference point. The impact of indirect and financing costs appears to dominate the FOAK build; this is in-line with observations at Vogtle and in the literature (Eash-Gates 2020). As more plants are built and construction timelines decrease, the relative contribution of financing costs to the total shrinks substantially. Both are strongly correlated with the construction duration. As more experience is accrued and plants are built faster, the impact of indirect and financing costs shrinks. It is also important to highlight how the diminishing returns that occur as best practices are fully implemented. Based on the current model assumptions, the OCC drop between plant 1 and 2 is 45% while the cost drop between plants 12 and 13 is diminished by only 1%. The model indicates that costs reductions stop being substantial after the fourth plant (cost reduction between 3–4 is 16% but is only 5% between 4–5). This highlights a threshold point at which overruns, reworks, and delays are avoided, and plants have reached well-executed status. After this point, cost reductions can still be observed by productivity gains, etc., but these appear to be much less pronounced than the avoidance of mistakes and overruns. This could be investigated in further work as potential design, construction, or operational changes (e.g., power uprates, better manufacturing approaches) may lead to further reductions as several plants are built (but should be avoided early-on to ensure the benefits of standardization are reaped).

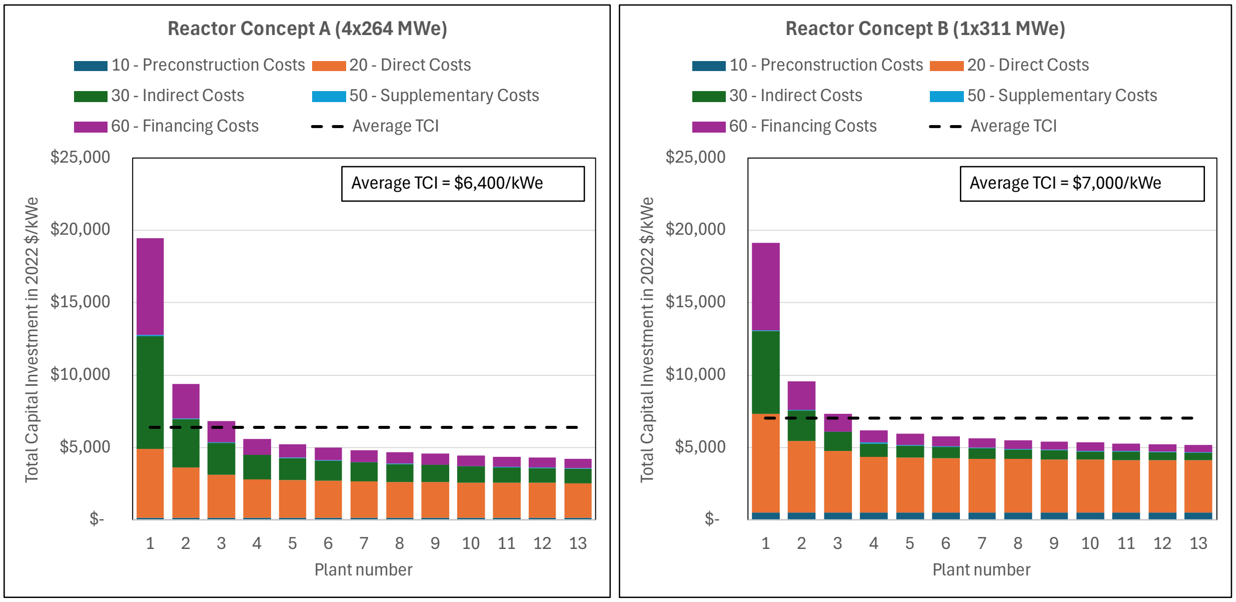
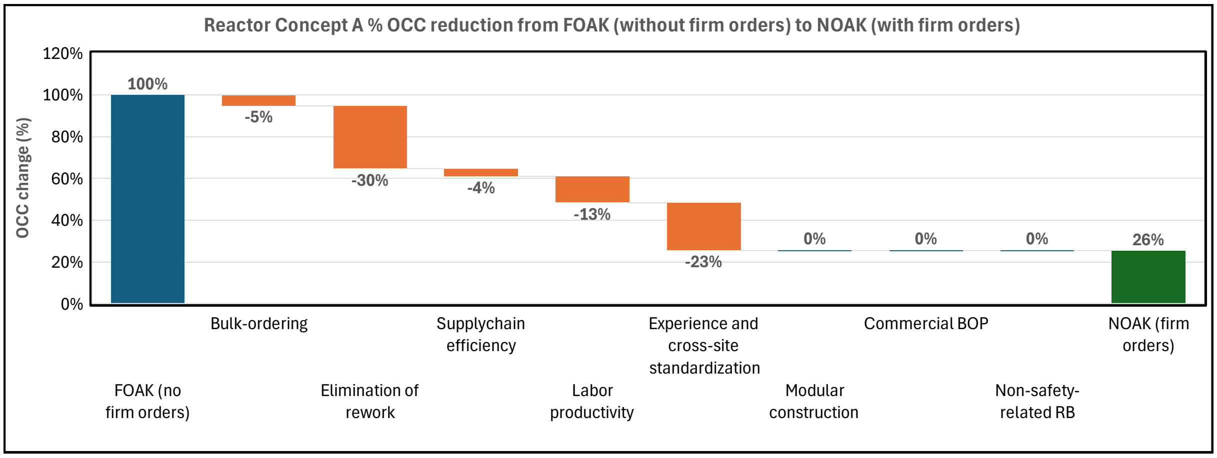


Figure 11. Breakdown of the TCI for Reactor Concept A (left) and Reactor Concept B (right) in Scenario 1. Results should not be used to contrast the two reactor types, as discussed in the text.

To better illustrate the contribution of various parameters on the overall cost reduction, Figure 12 provides a waterfall chart of each of their impacts. This maps the cost evolution from a single order FOAK to the bulk order NOAK for scenario 1 and shows the NOAK reductions achieved through various levers and variables. Under the assumptions selected here, the elimination of rework drives the biggest reduction in cost relative to the first plant. This is followed by the impact of experience and cross site standardization gained over building 13 reactors. Since under the chosen scenario, even the FOAK is assumed to have a non-safety BOP; hence, no impact is observed from that variable relative to the 13th plant in the order book.



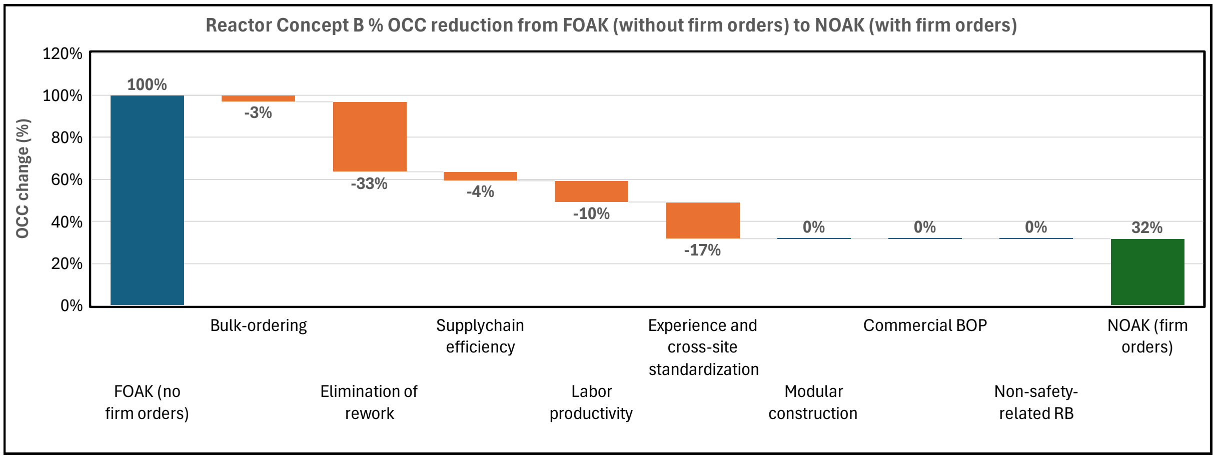


Figure 12. Waterfall chart showing impact of various levers on driving costs from a single-order FOAK to NOAK for Reactor Concept A (top) and Reactor Concept B (bottom) in Scenario 1.

4.2 Cost Reduction Scenarios

The framework was developed to be flexible enough for a user to evaluate cost changes for any given condition. There are substantial permutations of levers that users can explore to assess conditions that might best fit their given projections. As previously highlighted, while the costs vary between the two reactor concepts selected, care must be taken to not infer a determination on the competitiveness of a particular design over another. The framework incorporated two concepts simply to evaluate the potential impact of design-specific variations on cost trends. It is better interpreted as a design variability rather than a conclusive assessment of which design type is more competitive. Additionally, the more important aspect of these results is the cost reduction pathway achieved in each scenario (i.e., the percentage of cost reduction achieved from FOAK to NOAK) and the impact of different levers and variables.

For the purposes of this study, four potential scenarios were hypothesized to investigate the impact of various levers on projecting costs for nuclear technologies. The list of assumptions (and corresponding levers selected) is detailed below. The driving objective was to reach ‘cost-competitive’ OCC metrics across an order book. In the case of NOAK costs, this is defined as OCC < $3,600/kWe based on the target set by the DOE Liftoff report (DOE 2023). For the order book-wide average, this is defined as OCC between $4,000-5,000/kWe. This is based on several studies that seem to show that if nuclear energy OCCs approach this range, the technology could be more broadly competitive at the grid-scale (Cole 2023, Kim 2022). Based on these guidelines, the driving goal for the scenario evaluations was to verify if the least expensive plant met the $3,600/kWe target, and that the order book-averaged cost was within the $4,000-$5,000/kWe range.

Table 10 summarizes the different lever values inputted for the two design use cases. Minimum/maximum/average OCC and TCI results are provided across the order book in each of the tables to showcase the impact of levers on driving cost reductions as follows:

- **Scenario 1:** Based on the description in the previous section. This scenario is taken to be a realistic case in terms of project execution and overruns (but without the inclusion of an ITC), where some cost overruns are indeed experienced for the first few plants, and a reasonably sized order book of 13 plants was assumed. Innovations like a non-safety BOP and modular civil construction are assumed to occur from the first plant onward. Overall EPC proficiency before construction is taken to be low in some areas (e.g., A/E) and medium in others (e.g., construction proficiency).

  In this scenario, with the levers specified, the first plant OCC starts as high as $12,800/kWe for Reactor Concept A. The target of $3,600/kWe is reached after 11 plants are built, and the average OCC is just at the upper $5,000/kWe mark (see Table 10 for further information).

- **Scenario 2:** This is a more pessimistic scenario where design completion prior to start of construction is lower than the first scenario (60% versus 80%). This would be the case if the first build was rushed in light of timeline constraints for instance. Cross-site standardization is also lower (70% versus 80%), and the EPC has even less proficiency overall. The purpose of this scenario was to identify the increase needed in number of orders to bring the average OCC closer to the first scenario.

  Under this scenario with the levers specified, the first plant OCC now starts higher at $15,900/kWe for Reactor Concept A. The target of $3,600/kWe is reached after 15 plants are built, and the average OCC is just at the upper $5,000/kWe mark (see Table 10 for further information).

- **Scenario 3:** This scenario builds on the Scenario 1 but investigates the impact of ITC-like government support. The objective here is to drive down the order book-averaged OCC for one of the designs close to $4,000/kWe. As such, a 30% ITC plus 10% bonus (such as siting at the location of a retired/retiring coal-fired plant) is assumed for the first four plants deployed.

  Under these conditions, the first plant OCC with the inclusion of an ITC is now $8,000/kWe for Reactor Concept A. Since the tax credits do not impact the underlying performance, the target of $3,600/kWe is still reached after 11 plants are built. However, now the average OCC is at $4,100/kWe mark (see Table 10 for further information).

- **Scenario 4:** This is a relatively optimistic scenario. Here, lessons learned from the experience in Vogtle are incorporated early-on (DOE 2023). As such, design completion prior to start is set to 90%, EPC proficiencies are at a medium to high level (potentially assuming early investment in supply chain and leveraging international experience with nuclear construction), modular construction is applied, and both the BOP and RB are deemed non-safety by the NRC (based on functional containment approach). Lastly, an aggressive order book of 13 plants is committed to early-on, and 40% ITC is also obtained for the first three plants.

  In this scenario with the levers selected, the first plant OCC with ITC is now as low as $5,600/kWe for Reactor Concept A. The target of $3,600/kWe is still reached after 8 plants allowing the order book average OCC to even hit $3,700/kWe (see Table 10 for further information).

Table 10. Cost reduction results rounded to $100/kWe for Reactor Concepts A&B under the four scenarios considered in this study. Results should not be inferred to be exact projections nor used to compare two reactor technologies against one another, as discussed in the text.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
High-level descriptor	Realistic, no ITC	Pessimistic, no ITC	Realistic, with ITC	Optimistic, with ITC
Number Of Firm Orders	13	18	13	13
Design Completion	80%	60%	80%	90%
Design Maturity (0, 1, 2)	1	0	1	1
Supply Chain Proficiency (0, 1, 2)	0.5	0	0.5	1.5
A/E Proficiency (0, 1, 2)	0.5	0	0.5	1.5
Construction Proficiency (0, 1, 2)	1	1	1	1.5
Cross-Site Standardization	80%	70%	80%	80%
Modular Civil Construction	TRUE	TRUE	TRUE	TRUE
Commercial-Grade BOP	TRUE	TRUE	TRUE	TRUE
Non-Safety-Related RB	FALSE	FALSE	FALSE	FALSE: N=1 TRUE: N>1
ITC Amount	-	-	40%: N≤4 0%: N>4	40%: N≤3 0%: N>3
Interest Rate	6%	6%	6%	6%
Reactor Concept A				
Last plant (net) OCC ($/kWe)	$ 3,600	$ 3,600	$ 3,600	$ 3,400
First plant (net) OCC ($/kWe)	$ 12,800	$ 15,900	$ 8,000	$ 5,600
Av. (net) OCC w/ plant 1 ($/kWe)	$ 5,000	$ 5,000	$ 4,100	$ 3,700
Av. (net) OCC w/o plant 1 ($/kWe)	$ 4,300	$ 4,300	$ 3,800	$ 3,600
Last plant NCI ($/kWe)	$ 4,200	$ 4,200	$ 3,900	$ 3,900
First plant NCI ($/kWe)	$ 19,500	$ 25,700	$ 14,700	$ 9,500
Av. NCI ($/kWe)	$ 6,400	$ 6,500	$ 5,500	$ 4,800
First to last plant NCI ratio	4.61	6.06	3.49	2.40
Av. construction duration	77 months	77 months	77 months	73 months
Time for 5 sequential builds	15 years	16 years	15 years	14 years
Time for N sequential builds	25 years	33 years	25 years	24 years
Reactor Concept B				
Last plant (net) OCC	$ 4,700	$ 4,700	$ 4,700	$ 4,500
First plant (net) OCC	$ 13,100	$ 16,700	$ 8,300	$ 5,800
Av. (net) OCC w/ plant 1 ($/kWe)	$ 5,900	$ 5,900	$ 4,900	$ 4,600
Av. (net) OCC w/o plant 1 ($/kWe)	$ 5,200	$ 5,300	$ 4,700	$ 4,500

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Last plant NCI	$ 5,200	$ 5,200	$ 5,200	$ 5,000
First plant NCI	$ 19,100	$ 25,900	$ 14,300	$ 9,300
Av. NCI	$ 7,000	$ 7,200	$ 6,100	$ 5,500
First to last plant NCI ratio	3.67	4.98	2.75	1.86
Average construction time	43 months	43 months	43 months	39 months
Time for 5 sequential builds	9 years	10 years	9 years	8 years
Time for N sequential builds	14 years	19 years	14 years	13 years

The overall evolution of TCI from the first to the last plant in each scenario is shown in Figure 13 and Figure 14. The impact of tax credits in the last two scenarios are highlighted. Similarly to the discussion in the previous section, the cost drops are steep for the first four plants, then roughly reach a lower limit based on the assumptions of the framework used. This highlights how the model appears to be more sensitive to cost overrun levers (that lead to rework and delays) rather than cost reduction levers (such as experience-based efficiency, etc.).

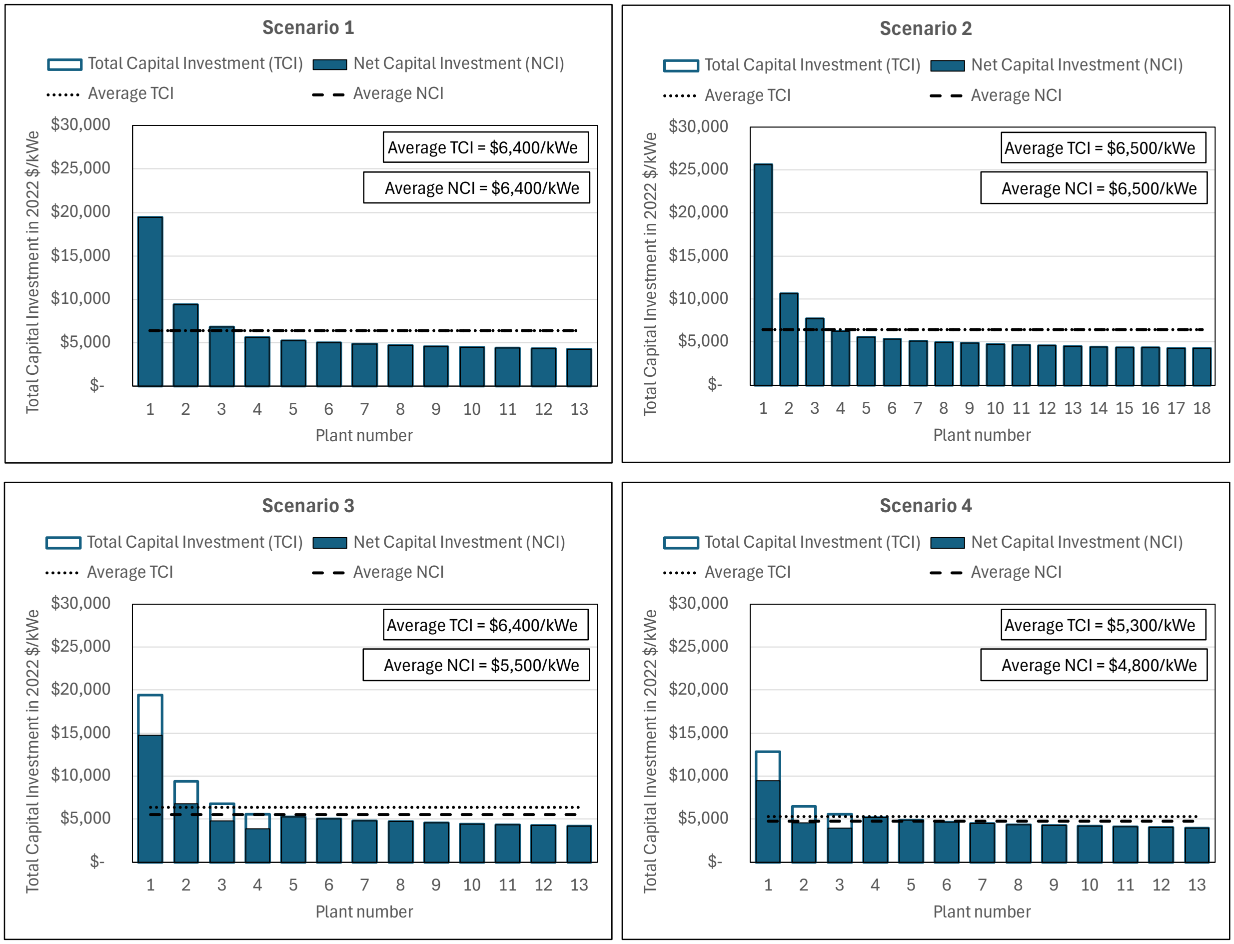


Figure 13. Breakdown of the Rector Concept A Total Capital Investment (TCI) in $/kWe for each plant in the four scenarios.

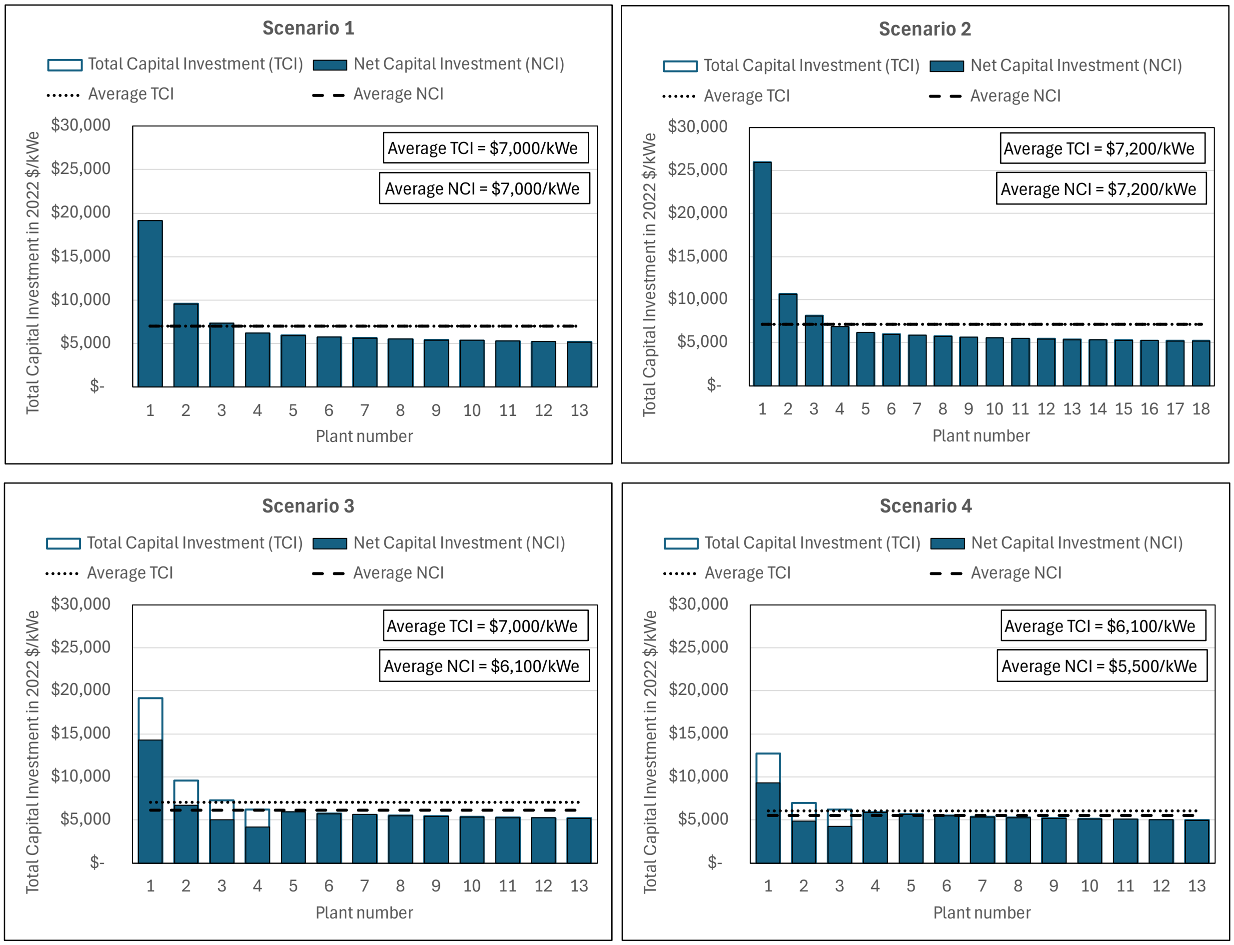


Figure 14. Breakdown of the Reactor Concept B Total Capital Investment (TCI) in $/kWe for each plant in the four scenarios.

Based on these scenarios, several important trends can be identified. The framework helps quantify the relative impact of bulk ordering. Taking Scenario 1 as an example: if all levers are left the same but the order book is shrunk to a single plant (as is the current case for the ARDP), the OCC increases to the $14,300 or 17,300/kWe for concepts A and B respectively. Comparing this to the first plant in Table 10, this is a 12-18% increase in OCC due to having a bulk order in place. The benefits from ordering 13 plants worth of equipment can be reflected directly in the first plant as shown here. This is because suppliers typically quote a fixed component price for a firm order of 13 plants, irrespective of when the plants are built. Note that the contribution to bulk order reduction in the waterfall chart in Figure 12 is slightly misleading since it shows the change in FOAK to NOAK, where the overall contribution of cost reductions is larger for things such as reworks etc. While the 12-18% change is between FOAK with and without bulk orders. Furthermore, averaging costs across a bulk order can lead to substantial cost reductions for the first movers. In Scenario 1, the average OCC is estimated to be ~60% lower than the single-plant build. This highlights the value of spreading costs across a large order book to help reduce the burden from overruns in the first few plants built.

Additionally, it is conceivable that large order books will materialize after the first plant of a given design is deployed. In the case of the two ARDP demonstrations, the costs for plant 1 are already accounted for. Similarly, the first AP1000 has already been deployed in the US. To highlight this variability, the order book-averaged OCC is shown with and without account for the first plant. In Scenario 1, not accounting for the first demonstration plant results in a 10-13% reduction in the averaged cost depending on the design. As a result, the scenario more closely meets the pre-defined ‘cost-competitiveness’ targets.

While the order book-averaged OCC values are relatively close in the first two scenarios, the minimum/maximum values differ. Essentially, to make up for poor execution up front in Scenario 2, the order book had to increase by 38% to 18 total plants committed to compensate for this. This showcases the different tradeoffs stakeholders will need to make when establishing consortia and committing to a number of plants. In some cases, stakeholders might be timeline constrained and unable to delay project start until the design is more complete or invest in readying the supply chain. While this will likely lead to cost overruns in the first several plants, it can be mitigated in the long term by expanding the number of participants in a consortium and broadening the order book.

Scenario 3 focused on evaluating the impact of government support (namely ITC). Currently, investment credits are anticipated to apply to the first plants deployed, but it remains unclear if the benefits would lapse prior to follow-on plants being constructed. Taking Scenario 1 as a starting point, with an order book-averaged OCC around $5,000/kWe for Reactor Concept A and $6,300/kWe for Reactor Concept B, Scenario 3 attempted to determine the impact of having more reactors qualifying for the tax credits and if the order book averaged costs could then approach $4,000/kWe for at least one of the design concepts. Assuming the first plants can replace coal-fired plant (which has an impact on the ITC amount), a 40% ITC is not unrealistic. At that level, if just the first 4 plants qualify for this level of ITC, then the order book average cost for Reactor Concept A design drops to ~$4,100/kWe and to ~$4,900/kWe for Reactor Concept B. Although the cost of concept B is higher, it can be compensated with a larger number of orders to achieve the same number of GW cumulative capacity since the concept B design selected for this study is smaller in size. This is a notable outcome since higher order book averages might deter several stakeholders from joining a consortium. While the duration of ITCs is dependent on a set timeline at this stage (or until CO_2 emissions drop to a certain level), this scenario assumes that the first four plants are able to be deployed within this timeframe. It is unclear at this stage if this will in fact materialize, but this assessment highlights the impact of ITC eligibility for more than the first demonstration plant.

It is interesting to note that under the assumptions for Scenario 3, the cheapest plant in terms of net OCC and NCI is now plant #4 rather than plant #13 (the last one built) due to the ITC support. This highlights how these credits can alter the dynamics for cost reduction. However, when the ITC is ignored, from an OCC and TCI perspective, the last plant is still the cheapest.

In Scenario 4, which is the most optimistic scenario, even without accounting for the impact of ITC, the first plant OCCs are already competitive against other clean energy sources. An FOAK OCC close to ~$9,000/kWe is reached for the two designs. This is brought down further to ~$5,500/kWe with ITCs. Note that with ITC applied, the FOAK net OCC is close to the NOAK OCC. Already, the first plant in this scenario is expected to be competitive across various markets in the United States. This would represent a best-case scenario where large order books are not entirely necessary. Nevertheless, with an ambitious order book of 13 plants, the averaged OCC for the Reactor Concept A reaches ~$3,700/kWe under these assumptions, close to the $3,600/kWe target of the DOE Liftoff report (DOE 2023). At these low levels of cost, nuclear energy can be expected to be widely attractive across the United States. In theory, it is not unrealistic to expect NPP costs could drop even further. Historical costs for U.S.-based nuclear constructions (escalated to 2022 USD) have been observed to reach levels lower than $2,000/kWe (SA&I 2017).

The framework also provided an estimate of the aggregate time to build the order book. As previously explained, 25% staggering of construction timeline between subsequent plants is assumed in this simplistic model. While additional plants can be built in parallel, limited learning will result hence cost reductions will not be as pronounced as shown in this model. Another way to interpret the timeline is: overall time needed to reach the projected cost reductions. Overall, the construction duration averaged around 6 years and 3 years for concepts A and B, respectively. It is important to recall that the variation between the two concepts is driven by the fact that Reactor Concept A considered is a 4-reactor plant with a higher power output. Based on the timeline assumptions in this study, a buildout of five operational plants (construction plus startup durations) would require between 8 to 16 years depending on the design and levers selected.

Overall, the different combination of levers in the scenarios considered highlight: (1) the overall potential for nuclear energy to achieve cost reductions and (2) the broad range of potential pathways toward that end-goal. Figure 15 shows that the order book-averaged net OCCs for all scenarios fall within $3,600–5,000/kWe range for at least Reactor Concept A. Nuclear energy can be expected to be attractive at any point within that range. This highlights the variety of approaches that can lead to competitive costs for the technology. The table also shows the ratio of FOAK to NOAK NCI across each scenario. It is interesting to note that the ratio is much less pronounced in Scenario 4. This is predominantly due to the better and 'optimistic' execution of the FOAK project as well as the impact of ITC that lower the FOAK costs. Nevertheless, an important conclusion here is to recognize that the cases with the highest starting point costs (e.g., Vogtle) typically have the largest potential for dramatic cost reductions in the long run (as also recognized in Shirvan 2022). As explained previously, avoidance of overruns (e.g., reworks, delays) can have an even greater contribution to cost reduction than productive steps toward driving down costs (e.g., modular construction). As mentioned earlier, while it may appear that improvements are larger for Reactor Concept A compared to Reactor Concept B, this is not due to the reactor technology. Rather it is driven by issues such as overall plant sizes, ratio of equipment/total costs, etc.

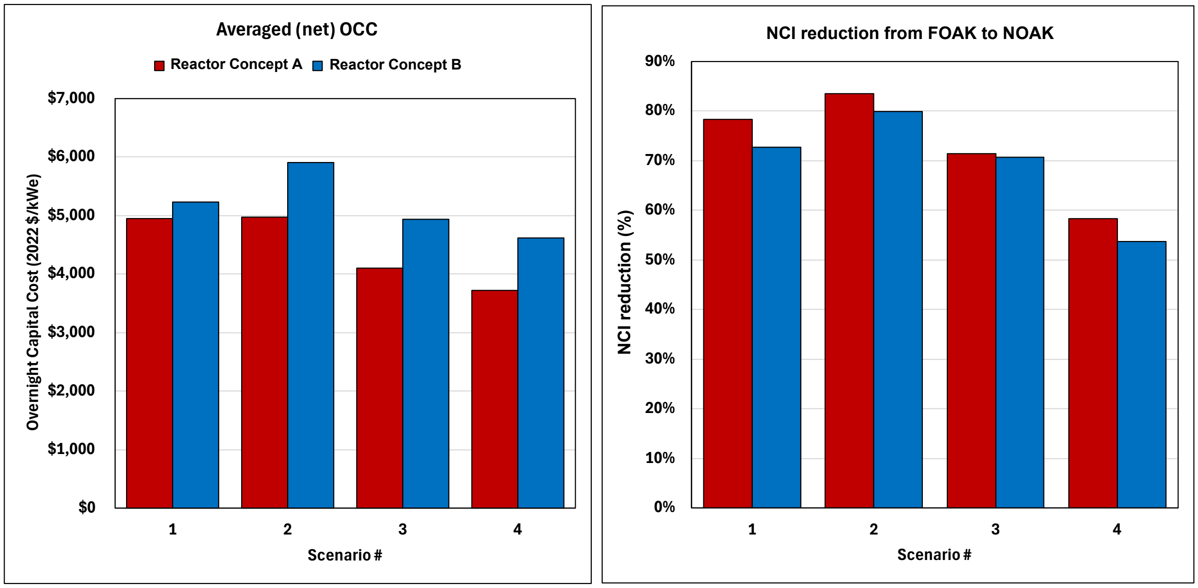


Figure 15. Comparison of the order book-averaged OCC and the percentage NCI reduction across the four scenarios.

4.3 Sensitivity Analysis on Cost Reductions

To better untangle the impact of several parameters on cost reductions, a sensitivity analysis was conducted. Figure 16 parametrizes the order book size for Scenario 1 (assuming all other levers are held constant). The resulting average OCC and NCI is then plotted as a function of the number of orders. Unsurprisingly, the average drops rapidly for an order book ranging from 4–20. The percentage change is not as pronounced beyond an order book size of ~12, but it is still important to reach NOAK values for nuclear in the ~$4,000/kWe range. Without any ITC, around 10–14 plants will need to be built to reach an order book average OCC below ~$5,000/kWe.

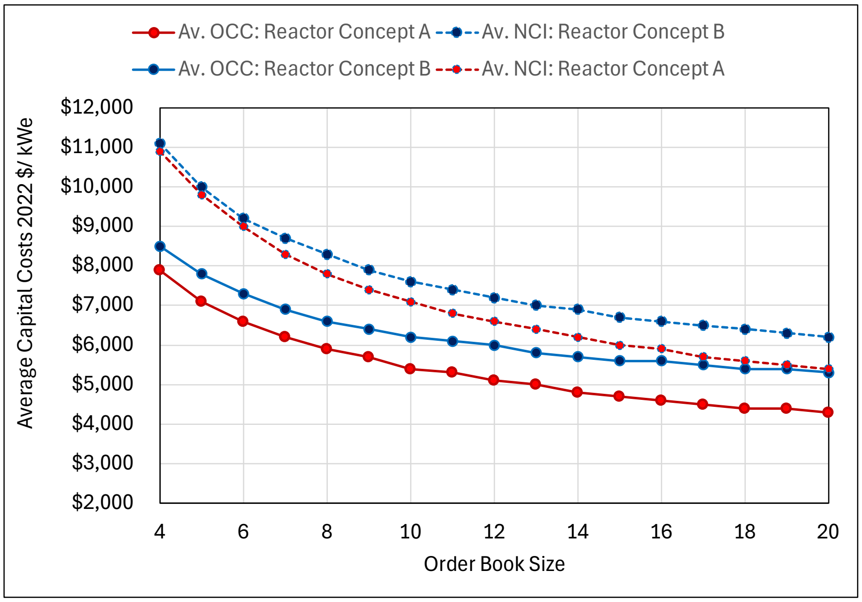


Figure 16. Sensitivity analysis of the order book size on the order book averaged OCC and NCI in Scenario 1.

In all the scenarios considered, the interest rate during construction was fixed at 6%. Figure 17 showcases the impact of this parameter on the NCI for Scenario 1 (the order book size is reset back to 13 plants). Interestingly, the concept A cost model appears to be more sensitive to the interest rate than in concept B. This is due to the difference in the construction duration in the two reactor concepts: the longer the duration of construction, the greater the financing costs. Overall, varying the interest rate across the range shown in Figure 17 can influence the NCI by as much as 35%. Nuclear energy is particularly sensitive to this parameter due to its high up-front capital investment and prolonged timeline for deployment. This highlights the potential benefits of securing low interest loans or similar government support by state or federal entities to help support new constructions. It is especially important for the first few plants built where construction durations are substantially longer, when these risks are at their highest.

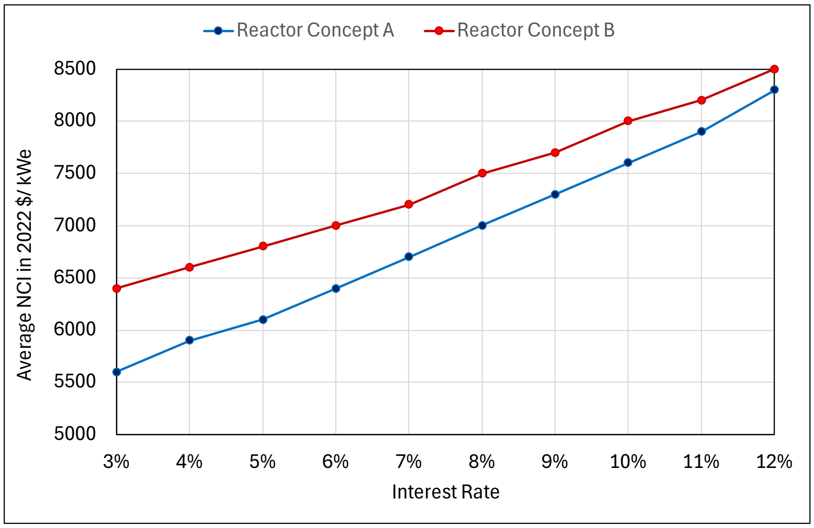


Figure 17. Sensitivity analysis of the interest rate during construction on the order book averaged NCI for Scenario 1.

The third parameter considered in this section is the EPC proficiency. This includes the levers, supply chain proficiency, A/E proficiency, and construction proficiency. The very low, low, medium, high, and very high EPC proficiency correspond to the A/E and supply chain proficiency levers set to 0, 0.5, 1, 1.5, and 2, respectively. The same EPC proficiency levels correspond to construction proficiency set to 1, 1, 1.5, 2, and 2, respectively. The two plots in Figure 18 below illustrate the significance of these set of levers in terms of OCC and NCI. Poor EPC execution can lead to delays, which drive up financing costs so much that the difference between the very low and very high cases can be as high as 25%. It should be recalled here that these levers are set for the first plant, and as more plants are built, the levers are assumed to improve as described in Section 3.3.2. Even with a starting point of low, a rating of high is achieved by plant 5.

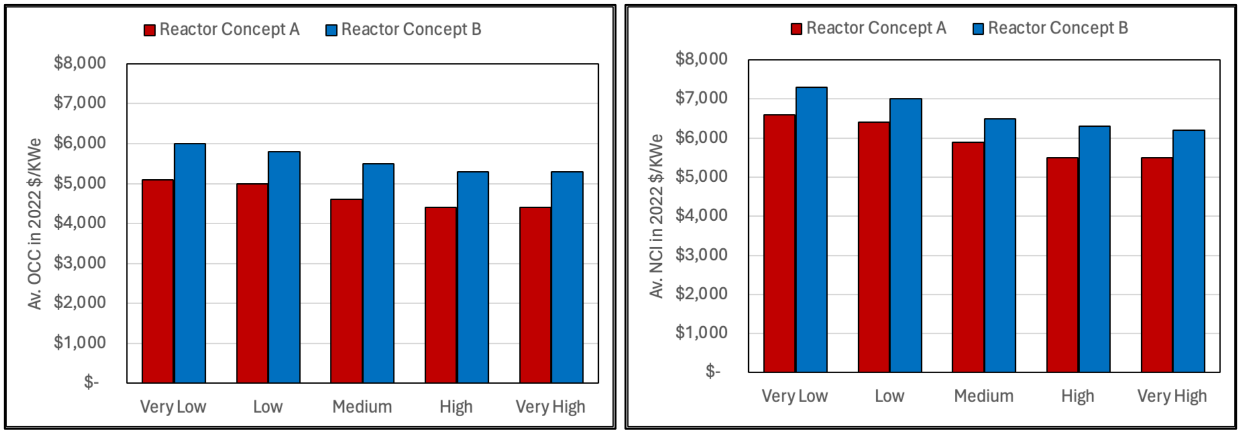


Figure 18. Sensitivity analysis of the EPC proficiency on the order book-averaged OCC and NCI in Scenario 1.

While levers can be more directly influenced by stakeholders, it is also important to look deeper and investigate the sensitivity of costs to the variables in the model. One significant parameter that impacts cost is the construction duration. In this work, the construction duration is defined to be dependent on other levers and variables, as depicted Figure 7. Construction duration increases due to supply chain delays and due to the increase in labor hours (because of reworking). The order book-averaged construction duration is also driven down by building more plants. To examine the sensitivity of the construction duration, the following ranges of levers are used, and the framework is run repeatedly in these ranges:

- Design completion: between 50-100%
- Design maturity: between 0-2
- Supply chain proficiency, the construction proficiency, design maturity, and the A/E proficiency: between 0-2
- Modularization: TRUE or FALSE
- Standardization: between 70-95%
- Commercial BOP and non-safety-related RB: TRUE or FALSE
- Number of orders: between 5-10.

A statistical sampling of 1,024 instances (scenarios) was conducted with levers within the range above. The impact of the order book-averaged construction duration on the OCC and NCI in these scenarios is shown in Figure 19 and Figure 20 respectively. As expected, and identified in the literature

(Hewlett 1986; Marciulescu 2019), OCC has a strong positive correlation with the construction duration. For both concepts, if the average construction duration increased by 20 months, the OCC increases by roughly 5,000 $/kWe. The NCI is even more sensitive to the increase in the construction duration since it includes financing costs. It increases by roughly 7,000 $/kWe if the construction duration increased by 20 months.

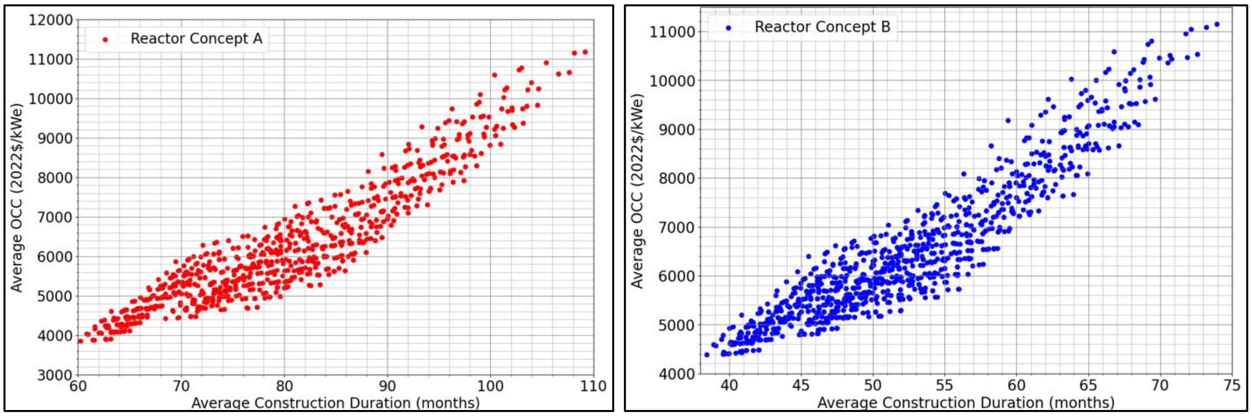


Figure 19. Sensitivity analysis of the construction duration on the order book-averaged OCC in Scenario 1 for Reactor Concept A (left) and Reactor Concept B (right).

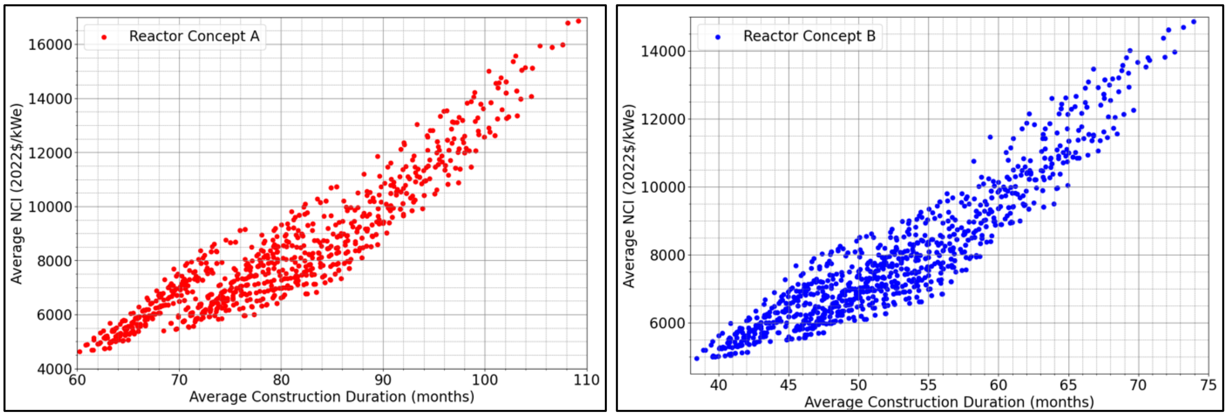


Figure 20. Sensitivity analysis of the construction duration on the order book-averaged NCI in Scenario 1 for Reactor Concept A (left) and Reactor Concept B (right).

For a broader assessment of sensitivities, the impact of each lever on the order book-averaged NCI is assessed in Figure 21. To evaluate the relative importance of each lever, the value of each lever was changed individually from the best to worst. The resulting NCI change (due to the change in the levers) is calculated with respect to the NCI of a hypothetical well-executed scenario. A hypothetical baseline scenario is based on the following assumptions:

- The number of firm orders is 20 (N=20).
- The design is 100% complete.
- The EPC proficiency is very high (corresponding levers set to 2).
- Design maturity is very high (= 2).
- Cross-site standardization is 95%.
- Both the BOP and RB are not deemed safety related (corresponding levers set to TRUE).

- The ITC is 40% (for the first 3 plants).
- The interest rate is 4%.

The purpose of this assessment is to identify the levers that the models were most sensitive to. Starting with this hypothetical baseline scenario, each lever was then changed individually to its respective ‘worst’ value as follows:

- Number of firm orders is 2 (N=2).
- Design completion is 50%.
- The EPC proficiency is very low (corresponding levers set to 0).
- Design maturity is very low (= 0).
- Cross-site standardization is 70%.
- The BOP is not commercial and is safety-grade (lever set to FALSE).
- The RB is safety-related and designed to perform containment function (lever set to FALSE).
- The ITC is 0% for all plants.
- The interest rate is 12%

For both reactor concepts, the most impactful lever is the number of orders – changing the number of orders from 2 to 20 plants increases the averaged NCI by ~$1,300/kWe for reactor concept A and $900/kWe for reactor concept B. This lever is followed by interest rate, which was set to a fixed value of 6% for all the scenarios considered in this study. A change of the interest rate from 4% to 12% increase the order book-averaged NCI by $800/kWe for concept A and more than $500/kWe for concept B. The NCI in concept A is more sensitive to the interest rate due to its longer construction duration. The next most impactful levers are cross-site standardization (~$600/kWe and ~$400kWe impact for concepts A and B, respectively), construction proficiency (~$300/kWe for both concepts) and ITC (~$250/kWe for both concepts). The rest of the levers have relatively small impact on the NCI.

The largest impact of the order book size reemphasizes the importance of forming large order books and validates the hypothesis identified by the DOE Advanced Nuclear Liftoff Report (DOE 2023). Given the long construction durations of nuclear, the high impact of interest rate is expected. Therefore, use of the interest rate lever can provide important information relevant to nuclear build decisions. The influence of cross-site standardization is also notable. Standardization and technologies that enable standardization such as seismic isolation can therefore play a key role in reducing the cost of nuclear in the long run. Construction proficiency also has a non-trivial impact on the NCI demonstrating the importance of construction execution on the cost and schedule. Although the impact of A/E and supply chain proficiency is smaller, the EPC services can collectively play a relatively large role (~$500/kWe) on the averaged NCI. This underlines the importance of good project execution.

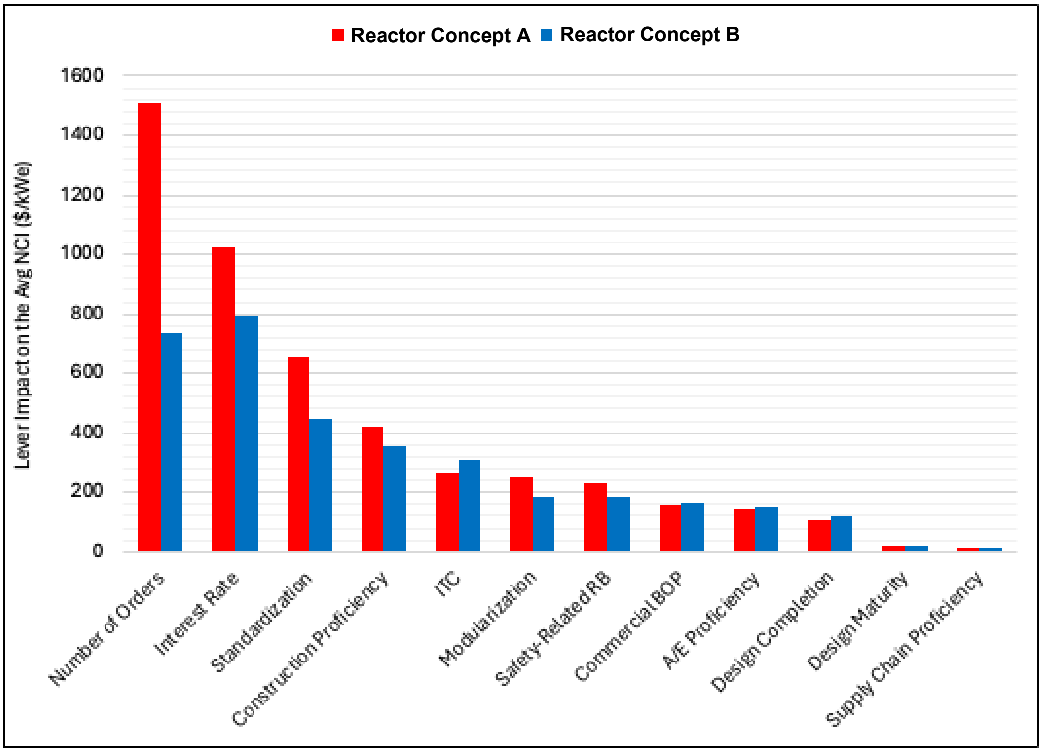


Figure 21. The impact of levers on the order book-averaged NCI for the two advanced reactor concepts.

5. FURTHER IMPROVEMENTS

As mentioned in Section 3.4, further work could build on this study and improve the underlying limitations of the framework while also expanding the analysis capabilities. On the first front, additional efforts could focus on addressing uncertainties within the framework, improving relationships, and considering more design solutions that are more representative of reactors being proposed (namely a smaller HTGR). One improvement that can be made in the framework is a better integration of levers to the construction schedule and total construction duration, which, as shown in the study, can have a significant impact on cost. This can be performed by connecting the framework to the TIMCAT scheduler tool directly. Another improvement would be a more explicit categorization of design specifications and cost reduction, namely more sophisticated correlations on the cost reductions on the site versus at a factory.

In terms of expanding the capabilities of the framework, one key item would be to allow users to adjust the time lag between the start of a plant relative to the next. Ideally, the staggering would be correlated with the EPC proficiency gains from one plant to the next. Too much overlap between the lead to little benefits, while too long of a lag may lead to a loss of know-how and workforce. Another important area of improvement is connecting the framework to the ACCERT software, thereby enabling users to both (a) perform cost estimation of new plant designs and (b) apply the cost reduction framework to these designs and visualize the progression of costs from FOAK to NOAK. The findings from this work can also be incorporated into the next update of Abou-Jaoude (2024) to provide a stronger foundation for cost reductions (rather than relying on a top-down learning rate approach).

6. SUMMARY AND CONCLUSIONS

This report presents the development of a framework that models the evolution of nuclear power plant (NPP) costs from first-of-a-kind (FOAK) to Nth-of-a-kind (NOAK) projects while accounting for several levers that have been identified in past literature as important cost drivers. While the results shown should be interpreted as ‘best estimates’, the framework can still enable stakeholders (government, utilities, etc.) to quantify the evolution of capital costs in different scenarios. Potential decisions are modeled in this framework through a set of 15 levers that can be categorized into three groups: government support (Investment Tax Credit [ITC] and land-related support through land costs), cost overrun levers (design completion before start of construction, design maturity, proficiency of architecture and engineering (A/E), supply chain, and construction companies), and cost reduction levers (design strategies that can reduce costs, such as: cross-site standardization, modularity in civil construction, and safety classification of the balance of plant and reactor building). With these levers as inputs, the framework outputs the overnight construction cost (OCC), total capital investment (TCI), and construction duration of all plants from FOAK to NOAK within a given order book size. The framework was applied to two advanced reactor design examples: a 4-reactor plant modeled primarily using data from the Next Generation Nuclear Plant (NGNP) program and a smaller, single-reactor plant modeled using PRISM design parameters. The framework was then used to evaluate four scenarios. The primary intent was to showcase the impact of placing bulk orders for new NPPs and spreading overall costs across several plants. These scenarios were designed to cover the range of optimistic, realistic, and pessimistic possibilities. All cases considered showcased different paths for mitigating the effects of large overruns in early-builds via bulk ordering and subsidies such as ITC.

Results of the study showed that the first few orders of NPPs, regardless of their design, will be expensive on a $/kW basis and will likely struggle to compete with other forms of energy generation without subsidies. This is not only due to FOAK overruns such as poor project execution, but also due to the capital involved in kickstarting a supply chain and a trained workforce. However, sharing these overruns through a consortium-led bulk order of plants can significantly reduce the financial risks involved even in the most pessimistic scenario of poor FOAK execution and bring the averaged OCC down below $5,000/kWe in one of the reactor concepts considered. For these scenarios, a larger bulk order might be required to negate the cost overruns in the first few plants, but when ITC is applied to these plants, a smaller bulk order might be sufficient to reach this end goal of OCC<$5,000/kWe.

The results also show that the reduction achieved by mitigating overruns in the first 4-5 plants overshadows the subsequent reduction gained by experience-based efficiency, especially when starting with lower proficiencies for contractors performing engineering, procurement and construction (EPC) services, and design maturity. This emphasizes the importance of good project execution, especially in the first few plants. It should also be noted that the impact of cost reduction levers is likely underestimated in the framework mainly since many of these levers will have a significant impact on schedule, which is currently modeled simplistically. A better understanding of the interaction between these two groups of levers, as well as the correlation between various levers in general can be a topic of a further study.

It should be noted that although comprehensive, this study hinges on several simplifying assumptions that introduce uncertainties in the estimates that are not captured here. However, users of the cost reduction framework developed in this study can easily modify the relationships based on their best judgment (or specific considerations) to model their own scenarios and draw their own conclusions. Nevertheless, the framework offers a convenient tool to better identify the barriers in achieving low nuclear costs through levers that are relatable to high-level considerations that stakeholders can make.

7. REFERENCES

AACE International (2020). "Cost Estimate Classification System - As Applied in Engineering, Procurement, and Construction for the Process Industries: Recommended Practice No. 18R-97." American Association of Cost Estimators (AACE) International.

Abou-Jaoude, A., Y. Arafat, A. Foss, and B. Dixon. 2021. “An Economics-by-Design Approach Applied to a Heat Pipe Microreactor Concept.” Technical Report, INL/EXT-21-63067, Rev. 000, Idaho National Laboratory, Idaho Falls, ID. https://doi.org/10.2172/1811894.

Abou-Jaoude, A., et al. 2022a. “Expansion of Cost Algorithm and Technoeconomic Assessment Capabilities.” Systems Analysis & Integration Campaign, INL/RPT-22-67852, Idaho National Laboratory, Idaho Falls, ID.

Abou-Jaoude, A., Y. Arafat, C. Bolisetti, B. Hanna, J. Belvedere, J. Blocker, B. Cooper, S. Harmon, and D. McCarthy. 2023. “Assessment of Factory Fabrication Considerations for Nuclear Microreactors.” Nuclear Technology, 209(11), 1697-1732. 10.1080/00295450.2023.2206779

Abou-Jaoude, A., L. M. Larsen, N. Guaita, I. Trivedi, F. Joseck, C. Lohse, E. Hoffman, N. Stauff, K. Shirvan, A. Stein. 2024. “Meta-Analysis of Advanced Nuclear Reactor Cost Estimations.” INL/RPT-24-77048, Idaho National Laboratory, Idaho Falls, ID.

Asuega, A., B. J. Limb, and J. C. Quinn. 2023. "Techno-economic analysis of advanced small modular nuclear reactors." Applied Energy, 334, 120669. 10.1016/j.apenergy.2023.120669

Atkins. 2016. “SMR Techno-Economic Assessment - Project 1 – SMRs: Comprehensive Analysis and Assessment, SMR TEA Report: Volume 1.” Atkins Limited and Ernst & Young LLP, July 21, 2016. https://assets.publishing.service.gov.uk/media/5a81c445ed915d74e33fff21/TEA_Project_1_Vol_1_-_Comprehensive_Analysis_and_Assessment_SMRs.pdf.

Boldon, L. and P. Sabharwall. 2014. “Small Modular Reactor: First-of-a-Kind (FOAK) and Nth-of-a-Kind (NOAK) Economic Analysis.” INL/EXT-14-32616, Idaho National Laboratory, Idaho Falls, ID. https://doi.org/10.2172/1167545.

Bolisetti, C., B. Hanna, J. Zhou, A. Abou-Jaoude, N. E. Stauff, and E. Hoffman. 2023. “Demonstration of ACCERT Software for Nuclear Power Plant Techno-Economics.”, Transactions: ANS Annual Meeting 2023, American Nuclear Society, Indianapolis, IN.

Buongiorno, J. 2021. “An Economic Evaluation of Micro-Reactors for the State of Washington.” *MIT Center for Advanced Nuclear Energy Systems*. MIT-ANP-TR-190 (January). https://canes.mit.edu/economic-evaluation-micro-reactors-state-washington.

Buongiorno, J., J. Parsons, and K. Dawson. 2018. “The Future of Nuclear Energy in a Carbon-Constrained World.” *MIT Energy Initiative.* https://energy.mit.edu/research/future-nuclear-energy-carbon-constrained-world/.

Cole, W., C. Murphy, J. Ho, J. Bristline, and A. Sowder. 2023. “The potential role for new nuclear in the U.S. power system: A view from electricity system modelers”, The Electrical Journal, 36, no. 2-3, https://doi.org/10.1016/j.tej.2023.107250.

Carelli, M. D., Garrone, P., Locatelli, G., Mancini, M., Mycoff, C., Trucco, P., and Ricotti, M. E. 2010. “Economic features of integral, modular, small-to-medium size reactors.” Progress in Nuclear Energy, 52(4), 403-414. 10.1016/j.pnucene.2009.09.003.

Delene, J. G. and C. R. Hudson, II. 1993. “Cost estimate guidelines for advanced nuclear power technologies.” ORNL/TM-10071/R3, Oak Ridge National Laboratory, Oak Ridge, TN. https://doi.org/10.2172/10176857.

Eash-Gates, P., M. M. Klemun, G. Kavlak, J. Mcnerney, J. Buongiorno, and J. E. Trancik. 2020. "Sources of Cost Overrun in Nuclear Power Plant Construction Call for a New Approach to Engineering Design." Joule, 4(11), 2348-2373. 10.1016/j.joule.2020.10.001

Forsberg, C., A. Foss, and A. Abou-Jaoude. 2022. “Fission Battery Economics-by-Design.” *Progress in Nuclear Energy*, vol. 152, (Oct. 2022): 104366. https://doi.org/10.1016/j.pnucene.2022.104366.

Froese, S., N. C. Kunz, M. V. Ramana. 2020. “Too small to be viable? The potential market for small modular reactors in mining and remote communities in Canada.” *Energy Policy*, vol. 144, (2020): 111587. https://doi.org/10.1016/j.enpol.2020.111587.

GA. 2007. "Pre-Conceptual Engineering Services for the Next Generation Nuclear Plant (NGNP) with Hydrogen Production: Executive Summary Report - NGNP and Hydrogen Production Preconceptual Design Studies Report." PC-000544, Rev 0, *General Atomics*. https://art.inl.gov/NGNP/NEAC%202010/INL_NGNP%20References/PC-000544%20Preconceptual%20Eng.%20Serv%20for%20NGNP.pdf.

Ganda, F., B. Dixon, E. Hoffman, T. K. Kim, T. Taiwo, and R. Wigeland. 2016. "Economic Analysis of Complex Nuclear Fuel Cycles with NE-COST." *Taylor & Francis, Nuclear Technology*, 193, no. 2 (Feb. 2016): pp. 219-233. https://doi.org/10.13182/NT14-113.

Ganda, F., G. Maronati, T. K. Kim, T. A. Taiwo, and R. Wigeland. 2017. "Report on Cost Estimation Algorithm for Advanced Nuclear Reactor Concepts." NTRD-FCO-2017-000469, Argonne National Laboratory, September 30, 2017.

Ganda, F., T. K. Kim, and T. A. Taiwo. 2018. "Report on the Update of Fuel Cycle Cost Algorithms." NTRD-FCO-2018-000439, Argonne National Laboratory. https://publications.anl.gov/anlpubs/2018/07/144923.pdf.

Ganda, F., E. Hoffman, T. A. Taiwo, T. K. Kim, and J. Hansen. 2019. "Report on the ACCERT Cost Algorithms Tool." ANL/NSE-19/10, Argonne National Laboratory. https://publications.anl.gov/anlpubs/2019/06/152862.pdf.

Gandrik, A. M. 2012. "HTGR Cost Model User's Manual." INL/EXT-11-23833, Idaho National Laboratory, Idaho Falls, ID. https://doi.org/10.2172/1034789.

Georgia Public Commission 2021. "Vogtle Units 3 and 4 Construction Monitoring Report."

GIF. 2007. "Cost Estimating Guidelines for Generation IV Nuclear Energy Systems." *Economic Modeling Working Group of the Generation IV International Forum*, FIG/#MWG/2007/004, Rev. 4.2, Sep. 26, 2007. https://www.gen-4.org/gif/jcms/c_40408/cost-estimating-guidelines-for-generation-iv-nuclear-energy-systems.

Gokcek, O., P. Babka, G. Pavlenco, and F. Kemmerer. 1995. "1994 Capital and Busbar Cost Estimate." GEFR-00940, *G. E. Nuclear Energy.* https://www.osti.gov/servlets/purl/1108730.

Grandy, C. and R. Seidensticker. (2007). "Advanced Burner Reactor 1000 MWth Reference Concept." ANL-AFCI-202, Argonne National Laboratory, Nuclear Engineering Division. Sep 30, 2007.

Guaita, N. and J. K. Hansen. Forthcoming. "Analyzing the Inflation Reduction Act and the Bipartisan Infrastructure Law for Their Effects on Nuclear Cost Data." INL/RPT-23-72925, Idaho National Laboratory, Idaho Falls, ID.

Hewlett, J., R. Cantor, and C. Rizy. 1986. An Analysis of Nuclear Power Plant Construction Costs. US Department of Energy (DOE/EIA-0485)

Hoffman, E., J. Zhou, N. Stauff, and A. Abou-Jaoude. 2022. "Costing and Technoeconomic Assessment Automation." ANL/NSE-22/61, August 30, 2022.

Hoffman, E., T. K. Kim, A. Abou-Jaoude, B. Dixon, A. Foss, and J. Hansen. 2021. "Expanded Cost Algorithm and Techno-economic Assessment Tools." ANL/NSE-21/27, June 30, 2021.

Holcomb, D. E., F. J. Peretz, and A. L. Qualls. 2011. "Advanced High Temperature Reactor Systems and Economic Analysis." ORNL/TM-2011/364. 2011, Oak Ridge National Laboratory, Reactor and Nuclear Systems Division. https://info.ornl.gov/sites/publications/files/Pub32466.pdf.

INL. 2012. "Assessment of High Temperature Gas-Cooled Reactor (HTGR) Capital and Operating Costs." TEV-1196, Rev. 1, Idaho National Laboratory, Idaho Falls, ID. https://art.inl.gov/NGNP/INL%20Documents/Year%202012/Assessment%20of%20High%20Temper ature%20Gas-Cooled%20Reactor%20-%20HTGR%20-%20Capital%20and%20Operating%20Costs.pdf.

Kim., T. K., et al. 2020. "Trial Application of TSRA and ACCERT Capabilities to Microreactor Designs." Argonne National Laboratory, ANL/NSE-20/20. July 31, 2020.

Kim, S. H. 2022. "Scenarios of Nuclear Energy Use in the United States for the 21st Century." PNNL-33234, Pacific National Laboratory, Richland, WA, https://www.pnnl.gov/publications/scenariosnuclear-energy-use-united-states-21st-century.

Komanoff, C. 1981. "Power Plant Cost Escalation: Nuclear and Coal Capital Costs, Regulation, and Economics." Van Nostrand Reinhold Publishing. https://www.komanoff.net/nuclear_power/Power_Plant_Cost_Escalation.pdf.

Lovering, J. R., A. Yip, and T. Nordhaus. 2016. "Historical construction costs of global nuclear power reactors." *Energy Policy* 91: 371–382. https://doi.org/10.1016/j.enpol.2016.01.011.

Lyons, R. E. 2019. "The Effect of Supply Chain Configuration on Small Modular Reactor Economics." Doctoral thesis, University of Cambridge.

McCabe, M. J. 1996. "Principals, Agents, and the Learning Curve: The Case of Steam-Electric Power Plant design and Construction." *The Journal of Industrial Economics* 44(4): 357–375. https://doi.org/10.2307/2950519.

McClure, P. R., D. I. Poston, V. R. Dasari, and R. S. Reid. 2015. "Design of Megawatt Power Level Heat Pipe Reactors." LA-UR-15-28840, Los Alamos National Laboratory, Los Alamos, NM. https://doi.org/10.2172/1226133.

McDonald, A., and L. Schrattenholzer. 2001. "Learning Rates for Energy Technologies." *Energy Policy* 29(4): 255–261. https://doi.org/10.1016/S0301-4215(00)00122-1.

Marciulescu, C., J. Reinder, R. Varrin, C. Marcks, E. Ingersoll, and A. Foss. 2019. "Advanced Nuclear Technology: Economic-Based Research and Development Roadmap for Nuclear Power Plant Construction. Electric Power Research Institute (EPRI).

Maronati, G. 2018. "Explaining Large Observed Variation in Construction Cost of Nuclear Power Plants Through Correlated Random Variables", Georgia Institute of Technology. May 2018. https://smartech.gatech.edu/bitstream/handle/1853/59904/MARONATI- DISSERTATION-2018.pdf?sequence=1&isAllowed=y.

McDowell, B. K. and D. Goodman. 2021. "Advanced Nuclear Reactor Plant Parameter Envelope and Guidance." NRIC-21-ENG-0001, PNNL-30992, *National Reactor Innovation Center*, Pacific Northwest National Laboratory. https://nric.inl.gov/wp-content/uploads/2021/02/NRIC-PPE-Guidance-Feb-2021-Final.pdf.

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

Moneghan, D., et al. 2024. "A Generic Nuclear Code of Accounts for Cost Estimation Standardization", Electric Power Research Institute Report No. 3002028937, and Idaho National Laboratory Report No. INL/RPT-24-76835.

Mooz, W. E. 1979. "Second cost analysis of light water reactor power plants." RAND Corp., Santa Monica, CA . https://www.osti.gov/biblio/5426641.

Munro, S., D. Foreman, D. McCarthy, I. Chambers, and T. Short. 2013. *Lean Design®: Value Quality Profit: 13th edition*. CreateSpace Independent Publishing Platform (2013). https://www.amazon.com/Lean-Design%C2%AE-Value-Quality-Profit/dp/1490594825.

NEI. 2019. “Cost Competitiveness of Micro-Reactors for Remote Markets.” *Nuclear Energy Institute*. https://www.nei.org/resources/reports-briefs/cost-competitiveness-micro-reactors-remote-markets.

Nuclear Energy Institute (2019a). "Risk-Informed Performance-Based Technology Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development." Modernization of Technical Requirements for Licensing of Advanced Non-Light Water Reactors, NEI-18-04 Revision 1, Nuclear Energy Institute (NEI), Washington, D.C.

OECD (2020). “Unlocking Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders” Organization for Economic Co-operation and Development, Nuclear Energy Agency.

Peres, M. 2017. “SMR Start: FOAK to NOAK.”

Prosser, J., M. Graham, Y. Acevedo, M. Jensen, B. D. James, and A. Abou Jaoude. 2023. First-Principles Cost Estimation of a Sodium Fast Reactor Nuclear Plant. United States: N. p., 2023. https://doi.org/10.2172/2007008.

Russo, G. V. 2010. “The Economics of Alternative Fuel Cycles on Sodium-Cooled Fast Reactors and Uncertainty and Sensitivity Analysis of Cost Estimates.” Master’s Thesis, 2010, *Massachusetts Institute of Technology*. https://dspace.mit.edu/handle/1721.1/62708.

Stewart, W. R. et al. 2020. “Pathways to Cost-effective Advanced Nuclear Technology.” *Energy Proceedings* 8. https://doi.org/10.46855/energy-proceedings-6880.

Stewart, W. R., Velez-Lopez, E., Wiser, R., and Shirvan, K. 2021. "Economic solution for low carbon process heat: A horizontal, compact high temperature gas reactor." Applied Energy, 304. https://doi.org/10.1016/j.apenergy.2021.117650

Stewart, R. W., J. Gregory, and K. Shirvan. 2022a. “Impact of modularization and site staffing on construction schedule of small and large water reactors.” *Nuclear Engineering and Design*, vol. 397 (Oct. 2022): 111922. https://doi.org/10.1016/j.nucengdes.2022.111922.

Stewart, W. R. and K. Shirvan. 2022b. "Capital Cost Evaluation of Advanced Water-Cooled Reactor Designs with Consideration of Uncertainty and Risk." MIT-ANP-TR-194, Center for Advanced Nuclear Energy Systems (CANES), Massachusetts Institute of Technology.

Stewart, W. R. and K. Shirvan. 2022c. “Capital Cost Estimation for Advanced Nuclear Power Plants.” *Renewable and Sustainable Energy Reviews*, vol 155 (2022): 111880 https://doi.org/10.1016/j.rser.2021.111880.

Shirvan, K. 2022. "Overnight Capital Cost of the Next AP1000." MIT-ANP-TR-193, Center for Advanced Nuclear Energy Systems (CANES), Massachusetts Institute of Technology.

Stewart, W. R., and Shirvan, K. 2023. "Construction schedule and cost risk for large and small light water reactors." Nuclear Engineering and Design, 407. 10.1016/j.nucengdes.2023.112305

117th U.S. Congress, 2021-2022. H.R.5376 – Inflation Reduction Act of 2022. Accessed April 27, 2023.

https://www.congress.gov/bill/117th-congress/house-bill/5376.

U.S. DOE. 1980. “Power Plant Capital Investment Cost Estimates: Current Trends and Sensitivity to Economic Parameters.” DOE/NE-0009, United States Department of Energy, Office of Nuclear Reactor Programs (June 1980). https://inis.iaea.org/collection/NCLCollectionStore/_Public/11/560/11560088.pdf?r=1.

U.S. DOE. 1987a. *“Technical Reference Book for the Energy Economic Data Base Program EEDBIX.”* DOE/NE-0092, United States Department of Energy, Office of Nuclear Energy.

U.S. DOE. 1987b. “Phase IX Update (1987) Report for the Energy Economic Data Base Program EEDB-IX.” DOE/NE- 0091, United States Department of Energy, Office of Programs Support.

U.S. DOE. 1987c. “Phase 9 update report for the Energy Economic Data Base Program EEDB-IX.” DOE/NE-0091, United States Department of Energy, *United Engineers and Constructors, Inc*. https://doi.org/10.2172/7227212.

U.S. DOE. 1987d. “Modular High-Temperature Gas-Cooled Reactor Plant Capital and Busbar Generation Cost Estimates.” DOE-HTGR-87-086, United States Department of Energy, *Gas-Cooled Reactor Associates*. https://doi.org/10.2172/713993.

U.S. DOE. 1988a. “Nuclear Energy Cost Data Base: A Reference Data Base for Nuclear and Coal-Fired Powerplant Power Generation Cost Analysis.” DOE/NE-95, United States Department of Energy, Office of Program Support.

U.S. DOE. 1988b. “Nuclear Energy Cost Data Base.” DOE/NE-0095, United States Department of Energy. https://inis.iaea.org/search/search.aspx?orig_q=RN:20013280.

U.S. DOE-NE SA&I. 2017. “Advanced Fuel Cycle Cost Basis Report.” United States Department of Energy, Office of Nuclear Energy Systems Analysis & Integration Campaign, https://fuelcycleoptions.inl.gov/SitePages/CostBasisReport.aspx. INL/EXT-17-43826, Idaho National Laboratory, Idaho Falls, ID. https://doi.org/10.2172/1423891.

U.S. DOE-NE SA&I. 2022. “Advanced Fuel Cycle Cost Basis Report: Module C3 High-Assay Low Enriched Uranium (HALEU) Enrichment and Deconversion/Metallization.” United States Department of Energy, Office of Nuclear Energy Systems Analysis & Integration Campaign NTRDFCO-2017-000265, Idaho National Laboratory.

U.S. DOE-NE SA&I. 2022. “Advanced Fuel Cycle Cost Basis Report: Module C3 High-Assay Low-Enriched Uranium (HALEU) Enrichment and Deconversion/Metallization.” United States Department of Energy, Office of Nuclear Energy Systems Analysis & Integration Campaign NTRDFCO-2017-000265, Idaho National Laboratory.

U.S. DOE. 2023. “Pathways to Commercial Liftoff: Advanced Nuclear.” https://liftoff.energy.gov/wp-content/uploads/2023/05/20230320-Liftoff-Advanced-Nuclear-vPUB-0329-Update.pdf.

U.S. NRC. 2010. “Report of Waste Burial Charges: Changes in Decommissioning Waste Disposal Costs at Low-Level Waste Burial Facilities.” NUREG-1307, Rev. 14, United States Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation. https://www.nrc.gov/docs/ML1032/ML103220151.pdf.

Vibrant Clean Energy (VCE). 2022. “Role of Electricity Produced by Advanced Nuclear Technologies in Decarbonizing the US Energy System.” https://www.vibrantcleanenergy.com/wp-content/uploads/2022/06/VCE-NEI-17June2022.pdf.

World Nuclear News. (2018, December). Cold testing complete at Barakah 3. https://www.world-nuclear-news.org/Articles/Cold-testing-complete-at-Barakah-3

Wright, Theodore Paul. 1936. “Factors Affecting the Cost of Airplanes.” Journal of the Aeronautical Sciences 3(4): 122–128. https://arc.aiaa.org/doi/10.2514/8.155.

J. Zhou, E. Hoffman, and N. E. Stauff. 2023. “Automating Algorithm Management and Techno-Economic Analysis of Nuclear Power Plants: Introduction to the ACCERT Software.”, Transactions: ANS Annual Meeting 2023, American Nuclear Society, Indianapolis, IN.

Appendix A

Excel Implementation of the Cost Reduction Framework

A-1. Excel Framework

The excel implementation of the cost reduction framework can be downloaded from: https://fuelcycleoptions.inl.gov/Shared%20Documents/Nuclear-Reactor-Capital-Cost-Reduction-Pathway-Tool.pdf or the ACCERT GitHub repository (https://github.com/accert-dev/ACCERT/tree/main/excel_framework). The excel file contains several sheets that are all hidden, but the main user interface of the framework is in the sheet named ‘Dashboard’ and contains tables with levers and the results (plots showing capital cost and construction duration evolution from FOAK to NOAK). The sheet contains levers and results for both Reactor Concept A and B. Users can change the input levers in this sheet (indicated in cells highlighted in blue) and see the result change in real time. Other sheets that hidden are as follows:

- ‘Concept A Results’ and ‘Concept B Results’ include the results that are used to create the plots on the Dashboard.
- ‘Concept A Relationships’ and ‘Concept B Relationships’ include all the coefficients in the relationships between levers, variables, and accounts.
- ‘Concept A Levers & Variables’ and ‘Concept B Levers & Variables’ includes the calculations of the levers and variables progressing from N=1 to N=N.
- ‘Concept A FOAK-to-NOAK’ and ‘Concept B FOAK-to-NOAK’ include the calculations that evolve the costs from FOAK to NOAK.
- ‘Concept A Financing’ and ‘Concept B Financing’ include the interest calculations based on the spend curves assumed.
- Other sheets include supporting calculations and data.

Appendix B

Accounts Included in the Cost Reduction Framework

B-1. List of Accounts

Table 11: List of accounts included in the cost reduction framework in the GN-COA format (Moneghan 2024).

Account #	Account title	Description
10	Capitalized Preconstruction Costs	
11	Land and land rights	This account includes the purchase of new land for the reactor site and land needed for any co-located facilities such as dedicated fuel cycle facilities. Costs for acquisition of land rights should be included.
13	Plant licensing	This account includes costs associated with obtaining plant licenses for construction and operation of the plant.
14	Plant permits	This account includes costs associated with obtaining all permits for construction and operation of the plant. This includes permits needed to support licensing (e.g., environmental review process to support an Environmental Impact Statement and FERC permits/approvals).
18	Other preconstruction costs	This account includes other costs that are incurred by the Owner prior to start of construction and may include site remediation work for plant licensing, or upgrades to public infrastructure, etc.
20	Capitalized Direct Costs	
21	Structures and improvements	This account covers costs for civil work and civil structures, mostly buildings, excluding the cooling towers.
22	Reactor system	This category is most dependent on the reactor technology being considered because the subaccount descriptions and costs depend heavily on the coolant used and whether the subsystems are factory-produced or constructed onsite. For today's LWRs, the entire nuclear steam supply system (NSSS) can be purchased as a unit from a reactor vendor. The reactor manufacturer may have its own COA structure for all the NSSS components. The list below attempts to be as generic as possible. The initial and reload fuel cores are not included here.
232.1	Energy conversion system	Includes turbine, generator, transformers, and other equipment required for generating electricity.
233	Ultimate heat sink	Includes condensers, cooling towers, water intake structures, pumps, and other equipment and structures used to reject heat not used by other processes.
24	Electrical equipment	Accounts 21 through 23 all have interfaces with the power plant electrical service system and its associated equipment. This equipment is located both inside and outside the main reactor/BOP buildings. (Note: The IAEA account system normally puts all I&C costs in this account. The EMWG decided to retain I&C costs within the accounts that require I&C equipment, mainly accounts 227 and 236.)
25	Initial fuel inventory	This account covers fuel purchased by the utility before commissioning, which is assumed to be part of the total

Account #	Account title	Description
		capitalized investment cost. In the United States, the initial core is not usually included in the design/construction (overnight) cost sum to which interest during construction (IDC; see below) is added. Because the first core, however, will likely have to be financed along with the design/construction/startup costs, its cost is included in overnight costs as part of capital at risk before revenues.
26	Miscellaneous equipment	Covers items not in the categories above.
30	Capitalized Indirect Services Costs	
31	Factory and field indirect costs	This account includes cost of construction equipment rental or purchase, consumables, and temporary structures used during construction.
32	Factory and construction supervision	This account covers the direct supervision of construction (craft-performed) activities by the construction contractors or direct-hire craft labor by the A/E contractor. The costs of the craft laborers themselves are covered in the labor-hours component of the direct cost in accounts 21 through 28 or account 31. This account covers work done at the site in what are usually temporary or rented facilities. It includes non-manual supervisory staff, such as field engineers and superintendents. Other non-manual field staff are included with Account 38, PM/CM Services Onsite.
33	Startup costs	This account includes costs incurred by the A/E, reactor vendor, other equipment vendors, and owner or owner's representative for startup of the plant.
34	Shipping and transportation costs	This account includes shipping and transportation costs for major equipment or bulk shipments with freight forwarding.
35	Engineering services	This account covers engineering, design, and layout work. Often preconstruction design is included here. These guidelines use the IAEA format for a standard plant (and equipment) design/construction/startup only and not the FOAK design and certification effort. (FOAK work is in the one-time deployment phase of the project and not included in the standard plant direct costs.) The design of the initial full size (FOAK) reactor, which will encompass multiple designs at several levels (preconceptual, conceptual, preliminary, etc.) will be a category of its own under FOAK cost. This account also includes site-related engineering and engineering effort (project engineering), required during construction of particular systems, which recur for all plants, and quality assurance costs related to design.
36	PM/CM services	This account covers the costs for project management and construction management support. It includes staff for quality assurance, office administration, procurement, contract administration, human resources, labor relations, project control, and medical and safety-related activities. Costs for craft supervisory personnel are included in account 32.

Account #	Account title	Description
50	Capitalized Supplementary Costs	
51	Taxes	This account includes taxes associated with the permanent plant, such as property tax, to be capitalized with the plant.
52	Insurance	This account includes insurance costs associated with the permanent plant to be capitalized with the plant.
54	Decommissioning	This account includes the close-out engineering costs and other costs to decommission, decontaminate, and dismantle the plant at the end of commercial operation, if it is capitalized with the plant.
60	Capitalized Financial Costs	
62	Interest	IDC is applied to the sum of all up-front costs (i.e., accounts 1 through 5 base costs). These costs are incurred before commercial operation and are assumed to be financed by a construction loan. The IDC represents the cost of the construction loan (e.g., its interest).

B-2. Breakdown of Costs into Accounts for Scenario 1

Table 12: Cost (in millions of 2022 USD) breakdown for 1st, 2nd, and 13th plants of Reactor Concept A in Scenario 1 as described in Section 4.

		N=1				N=2				N=13			
Construction duration (Month)		103				65							
Startup duration (Month)		16				11							
Account #	Account title	Factory Equipment	Site Material	Site Labor	Total	Factory Equipment	Site Material	Site Labor	Total	Factory Equipment	Site Material	Site Labor	Total
10	**Capitalized Preconstruction Costs**				**163**				**163**				**163**
11	Land and land rights				15				15				15
13	Plant licensing				107				107				107
14	Plant permits				5				5				5
18	Other pre-construction costs				36				36				36
20	**Capitalized Direct Costs**	**2,517**	**460**	**2,055**	**5,032**	**2,094**	**325**	**1,232**	**3,651**	**1,810**	**195**	**518**	**2,523**
21	Structures and improvements	137	351	1,046	1,533	109	247	618	974	90	148	250	487
22	Reactor system	1,478	32	466	1,976	1,176	23	289	1,488	972	15	133	1,120
232.1	Energy conversion system	234	-	96	330	187	-	60	247	154	-	29	183
233	Ultimate heat sink	73	9	64	145	58	6	38	102	48	4	15	67
24	Electrical equipment	43	39	153	236	34	28	91	153	28	17	37	82
25	Initial fuel inventory	452	-	-	452	452	-	-	452	452	-	-	452
26	Miscellaneous equipment	99	29	231	359	79	20	137	236	65	12	55	133
30	**Capitalized Indirect Services Costs**				**8,214**				**3,567**				**1,054**
31	Factory and field indirect costs				1,351				802				332
32	Factory and construction supervision				5,216				2,255				589
33	Startup costs				219				95				25
34	Shipping and transportation costs				18				8				2
35	Engineering services				1,409				406				106
50	**Capitalized Supplementary Costs**				68				41				**25**
51	Taxes				0				0				0
52	Insurance				60				32				17
54	Decommissioning				8				8				8
60	**Capitalized Financial Costs**				**7,069**				**2,496**				**960**
62	Interest				7,069				2,496				960
	Total Capital Investment (ΣCapitalCosts)				20,546				9004				4861

Table 13: Cost (in millions of 2022 USD) breakdown for 1st, 2nd, and 13h plants of Reactor Concept B in Scenario 1 as described in Section 4

		N=1				N=2				N=13			
Construction duration (Month)		103				65				30			
Startup duration (Month)		16				11				7			
Account #	Account title	Factory Equipment	Site Material	Site Labor	Total	Factory Equipment	Site Material	Site Labor	Total	Factory Equipment	Site Material	Site Labor	Total
10	**Capitalized Preconstruction Costs**				163				163				163
11	Land and land rights				-				-				-
13	Plant licensing				107				107				107
14	Plant permits				5				5				5
18	Other pre-construction costs				36				36				36
20	**Capitalized Direct Costs**	**1,482**	**96**	**748**	**2,325**	**1,190**	**64**	**425**	**1,679**	**959**	**35**	**150**	**1,144**
21	Structures and improvements	91	57	322	470	68	38	180	287	51	21	60	132
22	Reactor system	806	8	220	1,033	609	5	129	744	455	3	49	507
232.1	Energy conversion system	228	-	40	269	173	-	24	197	129	-	10	138
233	Ultimate heat sink	39	5	37	81	30	3	21	54	22	2	7	31
24	Electrical equipment	24	22	94	140	18	15	52	85	14	8	18	39
25	Initial fuel inventory	280	-	-	280	280	-	-	280	280	-	-	280
26	Miscellaneous equipment	15	4	34	53	11	3	19	33	8	1	6	16
30	**Capitalized Indirect Services Costs**				**2,194**				**810**				**171**
31	Factory and field indirect costs				331				191				70
32	Factory and construction supervision				1,416				506				82
33	Startup costs				60				21				3
34	Shipping and transportation costs				5				2				0
35	Engineering services				383				91				15
50	**Capitalized Supplementary Costs**				**23**				**14**				**14**
51	Taxes				0				0				0
52	Insurance				20				11				6
54	Decommissioning				2				2				8
60	**Capitalized Financial Costs**				**2,326**				**739**				**164**
62	Interest				2,326				739				164
	Total Capital Investment (ΣCapitalCosts)				**7,032**				**3,405**				**1,656**

Appendix C

Derivation of Correlations

C-1. Introduction

This appendix presents the assumptions and methods that were used to derive the correlations for variables such as the amount of reworking, labor productivity, and delays related to the supply chain.

C-2. Labor Productivity and Amount of Rework

The direct labor cost rise is impacted by the amount of reworking and the decrease in labor productivity. In this work, we assume that the labor productivity depends on the construction firm proficiency while the amount of reworking is dependent on three variables:

- The proficiency of the architecture and engineering (A/E) firms
- The proficiency of the construction firms
- The design completion before the beginning of the construction.

An equation for reworking is derived as follows:

$$R_{tot} = R_{AE} \times R_C \times R_{design} \tag{A-1}$$

where R_{tot} is the total reworking factor, R_{AE}, R_C, R_{design} are the reworking factor attributed to AE lack of proficiency, construction lack of proficiency, and design incompletion before the start of the construction. The values of the reworking factors (R_{AE}, R_C, R_{design}) are greater or equal to 1. If a reworking factor equals 1, there is no reworking. These three reworking factors are estimated in the following subsections.

C-2.1 Rework as a Result of A/E and Construction Proficiency

C-2.1.1 Direct Cost Change

Reworking leads to an increase in the labor hours, labor cost, material, and factory costs. For the sake of simplicity, it is assumed that reworking affects the component of the direct cost (factory, labor, and material costs) equally. Therefore, the change of the direct cost (account 20) attributed to the lack of proficiency of the A/E firms is expressed as:

$$\begin{aligned} &Change\ in\ direct\ cost\ =\ New\ direct\ cost - old\ direct\ cost \\ &= (R_{AE} - 1) \times (Cost_{20s-lab} + Cost_{20s-mat} + Cost_{20s-fac}). \end{aligned} \tag{A-2}$$

C-2.1.2 Construction Duration Change

A change in the direct labor cost leads to a change in the construction duration. Comparing the labor hours and total construction duration for previous nuclear projects (Stewart 2022b), it is noted that when the total labor hours increase by 5.4 times, the total construction duration increases by 2.2 times. Therefore, when the labor hours increase by the R_{AE} factor, the change in the construction duration is roughly estimated to be:

$$\frac{Construction\ druation\ in\ months\ (new)}{Construction\ druation\ in\ months\ (baseline)} = 0.3\ \times R_{AE} + 0.7. \tag{A-3}$$

C-2.1.3 Indirect Cost Change

From Section 3.2.3, the total indirect cost is estimated as a function of the direct cost and the construction duration to be:

$$Indirect\ cost = 0.785 \times \text{Direct Material Cost} \times \frac{\frac{Direct\ Labor\ Hours}{Construction\ Duration\ (months)}}{169280} + \text{Direct Labor Cost} \times [0.36 + 0.024 \times Construction\ Duration\ (months)]]. \tag{A-4}$$

Because of the reworking effect on material, labor and factors costs, the indirect cost changes. Applying the reworking factor and using Equation (A-3) for the construction duration change, the change in the indirect cost is estimated as:

$$\begin{aligned} &Change\ in\ indirect\ cost\ = \\ &\frac{0.00000464 \times \text{Direct Material Cost} \times Direct\ Labor\ hours}{construction\ duration\ (baseline)} \left(\frac{{R_{AE}}^2}{0.3 \times R_{AE} + 0.7} - 1 \right) \\ &\quad + 0.36 \times \text{Direct Labor Cost} \times (R_{AE} - 1) \\ &\quad + 0.024 \times \text{Direct Labor Cost} \times \text{Construction Duration (baseline)} \\ &\quad \times [R_{AE} \times (0.3 \times R_{AE} + 0.7) - 1]. \end{aligned} \tag{A-5}$$

C-2.1.4 Insurance Cost Change

The insurance cost scales with the sum of the direct and indirect cost change (Section 3.2.4). The change in the insurance cost change is.

$$\begin{aligned} &Change\ in\ insurance\ cost \\ &\quad = 0.0045 \times (change\ in\ direct\ cost + change\ in\ indirect\ cost). \end{aligned} \tag{A-6}$$

where the changes in direct and indirect costs are calculated in Equations (A-1 and A-2). Eventually, the change in the overnight cost is the sum of changes in direct, indirect, and insurance cost.

$$\begin{aligned} &Change\ in\ Overnight\ cost \\ &\quad = change\ in\ direct\ cost + change\ in\ indirect\ cost \\ &\quad + change\ in\ insurance\ cost \end{aligned} \tag{A-7}$$

C-2.1.5 Interest Cost Change

As presented in Section 3.2.5, the interest cost depends on the interest rate, overnight cost, construction duration, and startup duration. If the value of the reworking factor, R_{AE}, changes from 1 (i.e., no reworking) to 1.5 (corresponds to 50% reworking), the construction duration will increase according to Equation (A-3) by 15% to become 115 months (for Reactor Concept A) and 74 months (for Reactor Concept B). Using Equations (A-1 - A-7) and increasing the reworking factor to 1.5, the overnight cost will change relative to the baseline overnight cost (in Section 3.2) by 48% (for concept B) and 56% (for concept A).

Assuming that the interest rate is 6% and the startup duration to be 16 months, the cost of interest will increase by 80% (for concept B) and 67% (for concept A). Consequently, the total capital investment (TCI) would change too (see Figure 22).

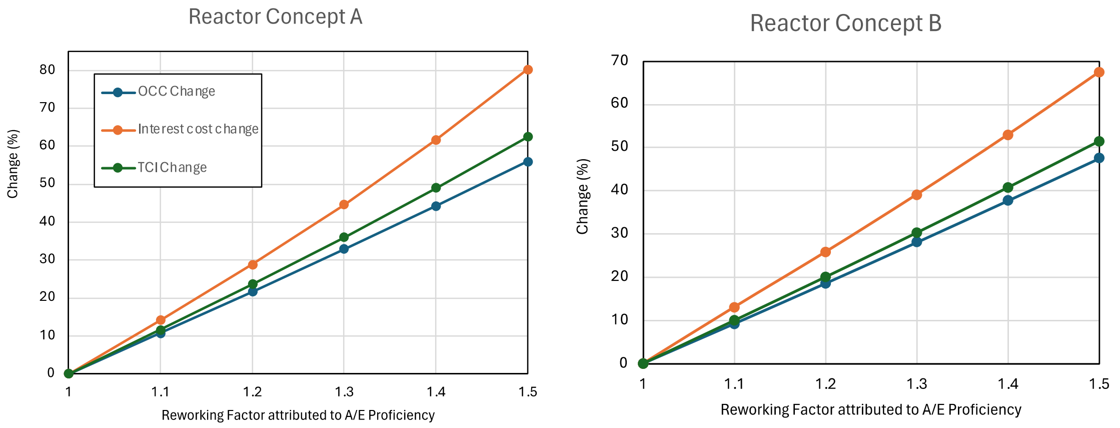


Figure 22. The change (%) in the cost of the total overnight capital cost, the cost of interest and the total capital investment (TCI) because of the amount of reworking. These plots are for Reactor Concept A (left) and Reactor Concept B (right) costs.

Using data from the literature (Hewlett, 1986), it is assumed the lack of proficiency of the A/E firm can increase the TCI by 30%. A 30% increase in TCI (in Figure 22) corresponds to a reworking factor of 1.3 (for concept B) and 1.25 (for concept A). In this work, it is assumed that the A/E proficiency ranges from 0 to 2. If the A/E proficiency equals 0, the TCI is assumed to increase by 30% (due to reworking), and when the A/E proficiency equals 2, the TCI does not increase (no reworking). Hence, a linear relationship between the A/E proficiency and the reworking factor attributed to A/E proficiency can be expressed as:

$$R_{AE}\ (for\ \text{concept B}) = -0.15 \times AE\ \text{proficiency} + 1.3 \tag{A-8}$$

$$R_{AE}\ (for\ concept\ A) = -0.125 \times AE\ proficiency + 1.25. \tag{A-9}$$

With the lack of data on how the construction proficiency can impact the cost overrun and reworking, it is assumed that the relationship between the construction proficiency and the resulting amount of reworking is similar to Equations (A-8 and A-9):

$$R_C\ (for\ concept\ B) = -0.15 \times construction\ \text{proficiency} + 1.3 \tag{A-10}$$

$$R_C\ (for\ concept\ A) = -0.125 \times construction\ proficiency + 1.25 \tag{A-11}$$

where the $construction\ proficiency$ takes values between 0 (lowest proficiency) and 2 (highest proficiency).

C-2.2 Labor Productivity as a Result of Construction Proficiency

The labor productivity is assumed to depend on the proficiency of the construction firm and take values between 0 and 1. The average labor productivity in the Vogtle nuclear project was 71% (Georgia Public Service Commission 2021). Hence, in this work, it is assumed that if the construction proficiency equals zero, the productivity is 0.71 while the productivity equals one if the construction proficiency equals 2. The productivity is expressed as:

$$Productivity = 0.145 \times construction\ proficiency + 0.71. \tag{A-12}$$

C-2.3 Rework as a Result of Inadequate Design Completion

The cost overrun in a nuclear project can be attributed to reworking and low productivity. Accounting for the total amount of reworking and the low productivity, equations for the change in direct cost, indirect cost and construction duration can be derived similar to Equations (A-2 to A-5).

$$\begin{aligned} &Change\ in\ direct\ cost \\ &\qquad = (R_{tot}-1)\times(Cost_{20s-mat}+Cost_{20s-fac}) \\ &\qquad + \left[\frac{R_{tot}}{productivity}-1\right]\times(Cost_{20s-lab}) \end{aligned} \tag{A-13}$$

$$\frac{Construction\ duration\ in\ months\ (new)}{Construction\ duration\ in\ months\ (baseline)} = 0.3\ \times\frac{R_{tot}}{productivity}+0.7 \tag{A-14}$$

$$\begin{aligned} &Change\ in\ indirect\ cost\ = \\ &\frac{0.00000464\times \text{Direct Material Cost}\times Direct\ Labor\ hours}{construction\ duration\ (baseline)}\left(\frac{{R_{tot}}^{2}/productivity}{\frac{0.3\ \times R_{tot}}{productivity}+0.7}-1\right) \\ &\qquad + 0.36\times\text{Direct Labor Cost}\times\left(\frac{R_{tot}}{productivity}-1\right) \\ &\qquad + \ 0.024\times\text{Direct Labor Cost}\times\text{Construction Duration (baseline)} \\ &\qquad \times\left[\frac{R_{tot}}{productivity}\times\left(\frac{0.3\ \times R_{tot}}{productivity}+0.7\right)-1\right] \end{aligned} \tag{A-15}$$

Similar to Section A.2.1, the change in the insurance cost and overnight cost can be estimated. Using the Vogtle project productivity (71%), the overnight cost would change (relative to the baseline value) with the total reworking factor (see Figure 23).

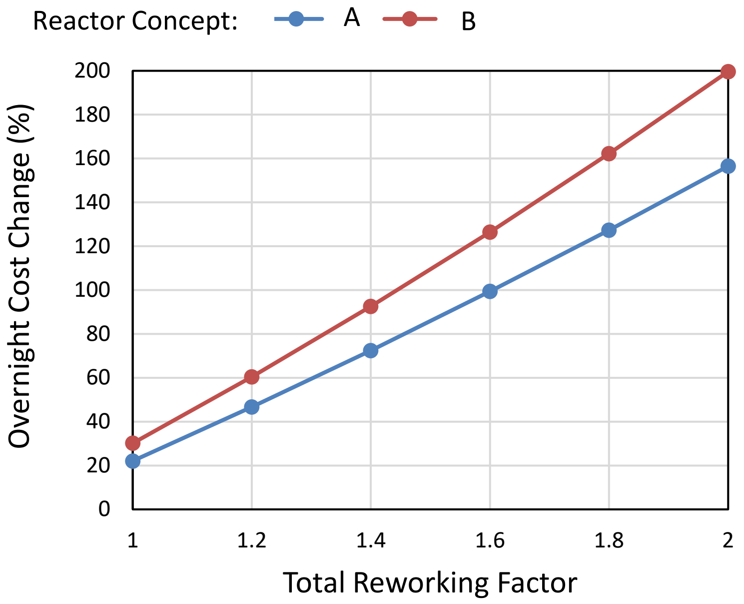


Figure 23. The change (%) in the total overnight capital cost because of the amount of reworking. All the costs are estimated at 71% productivity.

In the Vogtle project, the actual overnight cost was 2.45 times the initial cost estimate. In Figure 23, this cost overrun (145%) corresponds to a total reworking factor of 1.9 for Reactor Concept B. Using Equations (A-8) and (A-10) and if both the construction proficiency and AE proficiency equal 1, both the reworking factors R_C and R_{AE} equal 1.15. Hence, the reworking factor due to design incompletion is estimated from Equation (A-1) to be 1.45. Assuming that the design completion for Vogtle is 50%, a correlation between the design completion and the reworking factor can be estimated.

$$R_{design} \text{ (for Reactor Concept B)} = -0.9 \times design\ completion + 1.9 \tag{A-16}$$

Similarly, the correlation for the Reactor Concept A is

$$R_{design} \text{ (for Reactor Concept A)} = -0.69 \times design\ completion + 1.69. \tag{A-17}$$

C-3. Supply Chain Delays

For AP1000, 33% of components were delayed (Stewart 2022b), the average delay was 12 months (delays ranged between 6 to 18 months). Since the new components that do not have existing supply chain are more likely to be delayed, the supply chain delay is assumed to be dependent on the component design maturity. In this work, the design maturity is assumed to take values between 0 and 2. Hence, for each component, the expected supply chain delay is estimated to be 0, 6, and 12 months for design maturity value of 2, 1, and 0, respectively.

The supply chain experience of the firm can also impact the supply chain delays. Hence, an additional delay of 0, 3, and 6 months is estimated for the supply chain experience values of 2, 1, and 0, respectively. The dependence of the supply chain delays on the supply chain experience and design maturity is presented as:

$$\begin{aligned} &Supply\ Chain\ Delay\ (months) \\ &\quad = -6 \times design\ maturity - 3 \times supply\ chain\ experience + 18. \end{aligned} \tag{A-18}$$

A supply chain delay may or may not affect the total construction duration depending on the project schedule and the task dependencies. The schedule, duration of more than 200 tasks and the tasks dependencies from the EEDB PWR12-ME were downloaded from (Stewart 2022b) and from the TIMCAT software. The schedule was mapped from low-level accounts (3rd and 4th levels) to 2nd level accounts of both concepts considered. Figure 24 shows the task durations associated with accounts 21–26. The dependencies between these accounts are shows in Figure 25. Figure 25 also shows the needed completion fraction of each task before the next task starts.

It is assumed that the task durations associated with accounts 21–26 are $B_{21}, B_{22}, B_{23}, B_{24}, B_{25}, B_{26}$, and the corresponding supply chain delays are $D_{21}, D_{22}, D_{23}, D_{24}, D_{25}, D_{26}$. Using the dependencies shown in Figure 25, the times at which each task is completed are estimated to be:

$$\begin{aligned} T_{21} &= B_{21} + D_{21} \\ T_{22} &= 0.09 \times (B_{21} + D_{21}) + B_{22} + D_{22} \\ T_{23} &= 0.24 \times (B_{21} + D_{21}) + B_{23} + D\_23 \\ T_{24} &= 0.24 \times (B_{21} + D_{21}) + 0.34 \times (B_{23} + D_{23}) + B_{24} + D_{24} \\ T_{25} &= 0.18 \times (B_{21} + D_{21}) + B_{25} + D_{25} \\ T_{26} &= 0.21 \times (B_{21} + D_{21}) + B_{26} + D_{26}. \end{aligned} \tag{A-19}$$

The entire project will end after the completion of the tasks. If the project is completed at T_{end}, the construction duration will increase if T_{end} is larger than the initial baseline construction duration as follows:

$$\begin{aligned} T_{end} &= \max\left(T_{21}, T_{22}, T_{23}, T_{24}, T_{25}, T_{26}\right) \\ Updated\ construction\ duration &= max(\,baseline\ construction\ duration, T_{end}). \end{aligned} \tag{A-20}$$

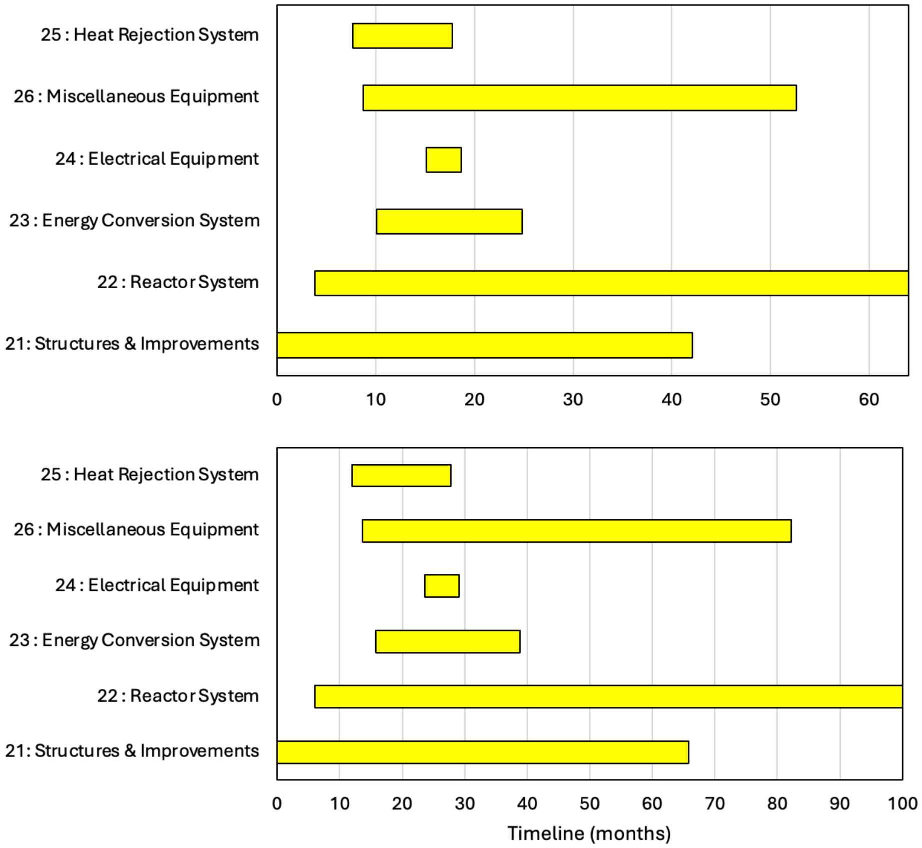


Figure 24. Estimated project timeline of Reactor Concept B (top) whose total construction duration is 64 months and Reactor Concept A (bottom) with 100 months construction duration.

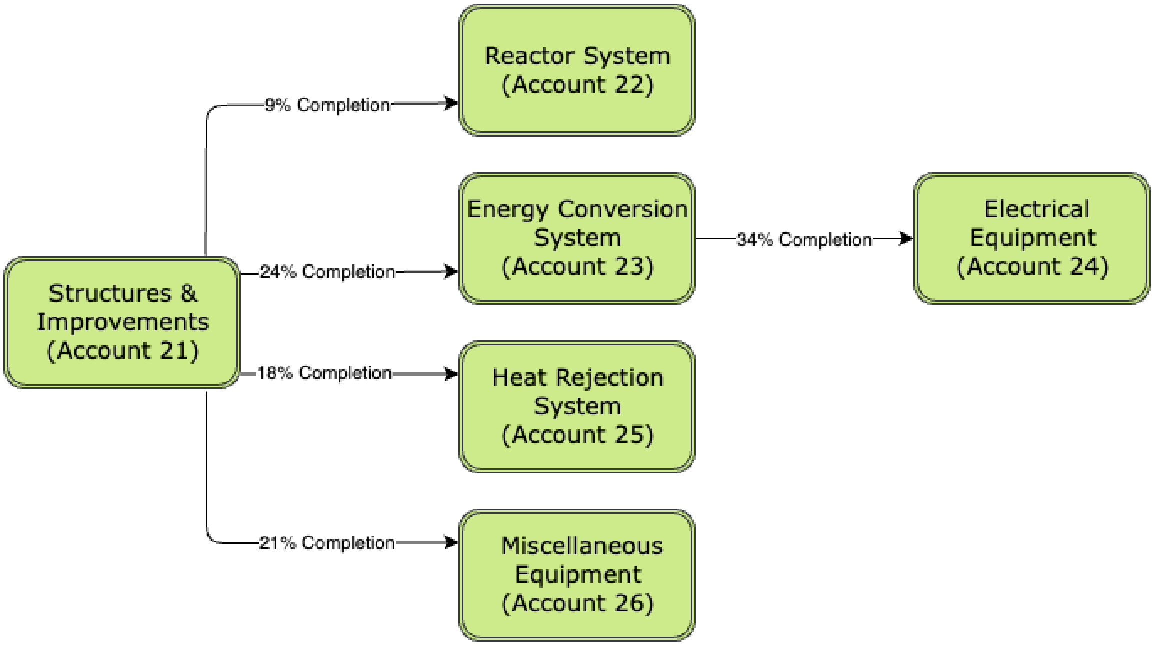


Figure 25. The dependencies between different tasks (accounts 21–26).