Advanced Nuclear Technology: Economic-Based Research and Development Roadmap for Nuclear Power Plant Construction

2019 TECHNICAL REPORT

Advanced Nuclear Technology: Economic-Based Research and Development Roadmap for Nuclear Power Plant Construction

3002015935

Technical Report, June 2019

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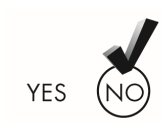

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ACKNOWLEDGMENTS

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Development and preparation of this report was sponsored by EPRI and funded, in part, by the U.S. Department of Energy via the Gateway for Accelerated Innovation (GAIN) Program, ClearPath, NuScale Power, and Nuclear Energy Institute (NEI).

EPRI appreciates and acknowledges the support of the following individuals, working collaboratively to support the development, and review of this report:

R. Baranwal	(GAIN)
T. Beville	(U.S. Department of Energy)
L. Braase	(GAIN)
M. Brasel	(NuScale Power)
A. Conner	(Idaho National Laboratory)
R. King	(EPRI)
S. Nelson	(ClearPath)
M. Nichol	(Nuclear Energy Institute)
D. Scott	(EPRI)

This publication is a corporate document that should be cited in the literature in the following manner:

Advanced Nuclear Technology: Economic-Based Research and Development Roadmap for Nuclear Power Plant Construction. EPRI, Palo Alto, CA: 2019. 3002015935.

ABSTRACT

Public and private sector interest in nuclear reactor technologies is growing as utilities and other energy suppliers seek options for scalable, dispatchable, concentrated, and non-emitting energy generation. In the U.S. and the rest of the world, the need for nuclear power has been highlighted in many high-level studies that focus on topics ranging from national and international security, to the importance of nuclear as a carbon free, reliable, and resilient energy source.

However, cost overruns and schedule delays experienced during recent nuclear power projects and other large construction projects must be addressed. Analysis of recent nuclear projects (U.S., Europe, and non-Western regions) has shown similarities among successful projects and challenges shared by projects that went over budget, did not meet construction schedule targets, or both.

This report identifies methods and technologies that could enable a reduction in cost for new nuclear plants and develops a cost estimation tool that can be used to determine the main cost drivers. Drivers for both first of a kind (FOAK) and Nth of a kind (NOAK) construction are considered, but the cost estimation tool is based on NOAK.

The cost estimation tool incorporates lessons learned from recent projects and can potentially help future owner-operators allocate their funding and invest in technologies that can substantially decrease the cost of new nuclear plants. Six general categories were defined, based on the primary way the technology reduces cost, and the tool was used to assess the financial savings resulting from the implementation of a variety of technologies.

For each identified cost driver, a roadmap was developed to show the timeline over which technology would need to be developed and deployed to substantially reduce the cost of new plants. The cost estimation tool was then used to estimate the contribution that each area could have in reducing the Overnight Construction Cost (OCC) and the Levelized Cost of Electricity (LCOE) for new nuclear power construction.

Keywords
Advanced Nuclear Technology
Economic Roadmap for New Nuclear Reactors
Levelized Cost of Electricity
Nuclear Costs Estimating Tool
Overnight Construction Costs

ELECTRIC POWER RESEARCH INSTITUTE

EXECUTIVE SUMMARY

Deliverable Number: 3002015935

Product Type: Technical Report

Product Title: Advanced Nuclear Technology: Economic-Based Research and Development Roadmap for Nuclear Power Plant Construction

PRIMARY AUDIENCE: Utilities, technology developers, policymakers, investors, and other stakeholders who want to understand potential cost drivers, economic barriers, and potential cost reductions for new nuclear reactors

SECONDARY AUDIENCE: General public and industry partners with an interest in understanding the economic factors for new nuclear reactors

KEY RESEARCH QUESTION

Cost overruns and schedule delays experienced during recent nuclear power plant projects must be reviewed and addressed.

EPRI seeks to answer the fundamental questions:

- What are the main cost drivers for new nuclear plants?
- What cost estimation methods, technology gaps, and roadmaps exist or are needed to enable a reduction in the cost of new nuclear construction?
- What are the estimated financial impacts of implementing specific and targeted R&D to provide the highest cost-benefit to new nuclear construction?

RESEARCH OVERVIEW

In keeping with its previous leadership role in the commercialization of advanced light water reactors (ALWRs)—and in collaboration with relevant stakeholders from the advanced nuclear community—EPRI has developed a cost estimation tool that can be used to determine the main cost drivers for new nuclear plants.

This cost estimation tool, intended to be used for an "Nth of a Kind" (NOAK) reactor, was developed using a deterministic bottom-up modeling approach and drew mainly from the DOE's Energy Economic Database (EEDB) program. In parallel with the model development, industry experts contributed ideas for cost drivers and what solutions might be used to address them. Although the codes of accounts are organized by components and grouped by direct and indirect costs, the surveyed industry experts phrased their cost drivers as concepts that extended across multiple Code of Accounts (COAs) with solutions that decreased costs in multiple ways (e.g., schedule reduction, increases to craft-labor productivity, reductions in managerial labor expenses, lower material costs and quantities, etc.).

Generic technologies were then evaluated to provide representative examples and illustrate the potential cost savings that could be achieved through the implementation of a specific technology. Also, for each identified cost driver, a roadmap was developed to show the timeline over which technology would need to be developed and deployed to substantially reduce the cost of new plants.

KEY FINDINGS

- The most significant cost reduction strategies found were those that were able to reduce construction duration, in addition to the savings in labor and to a lesser extent, the savings in materials. These savings are further amplified when accounting for reduced interest costs.
- Civil and structural design was also found to be a significant cost driver, largely because any advancements in this area have the potential to decrease the construction duration. Over half of the potential cost savings ($456/kWe out of $892/kWe) in this cost driver are a result of schedule reduction.
- The cost of materials was perceived or assumed to be a major cost driver. However, the results show that reducing the cost of all plant materials by 50% would only result in $343/kWe of savings ($258/kWe in materials and $125/kWe in indirect costs).
- It was estimated that the lack of constructability affects $2338/kW of total overnight construction cost (OCC). Roughly half of this is structures and improvements, while the other half is distributed across other COAs.
- If existing technologies are used to improve all five of the quantitatively assessed cost drivers, there is an opportunity to reduce costs by $2079/kW from the existing baseline OCC of $5500/kW, **resulting in a potential OCC cost of $3421/kW**.
- Consistent with the findings of other studies, the direct cost of the nuclear island was found to be less than 20% of all direct costs.
- Many cost overruns during plant construction occur because the FOAK plant designs are not 100% completed prior to beginning construction. There is a strong negative correlation between OCC and percent design completion.
- Labor cost was determined to be the largest cost driver and inspection delays are one of the identified reasons that contributes to reduced worker productivity in nuclear construction.

WHY THIS MATTERS

As the U.S. and global power sectors continue to evolve and incorporate higher levels of variable renewable energy, demand-side flexibility, and distributed generation, greater emphasis is placed on the dispatchability and reliability of grid resources. New nuclear reactor designs offer options that could meet these needs.

Understanding the main cost drivers and the potential savings that could be achieved by implementing specific technologies, could help guide future R&D and focus on existing gaps that prevent new nuclear to be deployed in a more economical manner.

HOW TO APPLY RESULTS

These results, focused primarily on mitigating risks specific to NOAK construction, can inform utilities, potential owners, investors, and technology developers in their decisions regarding a more economically viable development and deployment of new nuclear reactors. They can also provide a better understanding of the existing challenges and opportunities related to the development and deployment for new nuclear power plants.

Additional savings could be achieved by addressing the cost drivers for which a quantitative analysis was not done, assuming more aggressive cost reductions for the analyzed cost-drivers, or assuming that schedule reductions from reduced craft labor costs (increases in worker productivity) and improved civil/structural design are not mutually exclusive.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- EPRI has established a Technical Advisory Committee (TAC) under the Advanced Nuclear Technology (ANT) Program, to provide a forum for exchanging information and obtaining input on the direction and nature of EPRI's ANT strategic focus and research and development for advanced nuclear power plants.
- Users of this report may be interested in the Construction Speed and Quality Technical Advisory Group (TAG). Contact Hasan Charkas at 704.595.2645 or hcharkas@epri.com for additional information.

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PROGRAM: Nuclear Power, P41 and Advanced Nuclear Technology, P41.08.01

IMPLEMENTATION CATEGORY: Strategic-Long Term

ACRONYMS

AACE	Association for the Advancement of Cost Engineering
AEC	Atomic Energy Commission
AI	Artificial Intelligence
ALWR	Advanced Light Water Reactor
AMM	Advanced Materials and Manufacturing
ANL	Argonne National Laboratory
ANT	Advanced Nuclear Technology
ATF	Accident Tolerant Fuel
BC	Base Cost
BIM	Building Information Modeling
BOCI	Balance of Conventional Island
BONI	Balance of Nuclear Island
BOP	Balance of Plant
C&IO	Commissioning and Initial Operations
CCI	Construction Cost Indexes
CCS	Carbon Capture and Storage
CERA	Power Capital Cost Index Database
COA	Code of Accounts
CPI	Consumer Price Indicator
DC	Direct Costs
D&D	Deactivation and Decommissioning
DG	Diesel Generators
DOE	Department of Energy
ECI	Engineering and Construction Innovation
EEDB	Energy Economic Database Program (by DOE as supported by ORNL and UEC)

EIA	Energy Information Administration
EMWG	Economic Modeling Working Group
ENR	Engineering News-Record
EOC	End of Cycle
EPIC	Energy Policy Institute of Chicago
EPRI	Electric Power Research Institute
EPZ	Emergency Planning Zone
ETI	Energy Technologies Institute (UK Study)
EU	European Union
FOAK	First of a Kind
FOAKE	First-of-a-Kind Engineering
FOM	Figure of Merit
FP	Friction Pendulum
FW	Feedwater
GAIN	Gateway for Accelerated Innovation in Nuclear
GDP	Gross Domestic Product
GPR	Ground Penetrating Radar
GW	Giga Watt
HDPE	Hugh Density Polypropylene
HP	Horsepower
IAEA	International Atomic Energy Agency
IDC	Interest During Construction
IGCC	Integrated Gasification Combined Cycle
IPD	Integrated Project Delivery
IPWR	Improved Pressurized Water Reactor
IPWR12	Improved PWR12 Model
IT	Information Technology
KPI	Key Performance Indicator
LCOE	Levelized Cost of Electricity
LDEGC	Levelized Discounted Electricity Generation Costs
LDR	Low Damping Rubber

LNT	Linear No-Threshold
LPS	Last Planner System
LRAC	Long Range Average Cost
LUEC	Levelized Unit Electricity Cost
LUPC	Levelized Unit Power or Production Cost (for process heat)
LWR	Light Water Reactor
MAS	Modular Assembly Site
MCR	Main Control Room
MH	Man Hours
NDE	Nondestructive Examination
NEI	Nuclear Energy Institute
NI	Nuclear Island
NOAK	Nth of a Kind
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
NRE	Non-Recurring Engineering
NSSS	Nuclear Steam Supply System
O&M	Operating & Maintenance
OC	Owners Costs
OCC	Overnight Construction Cost
OECD	Organization for Economic Co-operation and Development
ORNL	Oak Ridge National Laboratory
P&ID	Piping and Instrumentation Diagram
PHA	Process Hazard Analysis
PHWR	Pressurized Heavy Water Reactor
PRA	Probabilistic Risk Assessment
PWR	Pressurized Water Reactor
QA	Quality Assurance
QC	Quality Control
RCA	Radiation Controlled Area
SDD	System Design Description

SMR	Small Modular Reactor
TCIC	Total Capital Investment Cost
TG	Turbine Generator
TMI	Three Mile Island
US-REGEN	U.S. Regional Economy, Greenhouse Gas, and Energy
UHS	Ultimate Heat Sink
UT	Ultrasonic Testing
WACC	Weighted Average Cost of Capital

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1
INTRODUCTION

In the 1970s and 1980s, various organizations regularly updated the existing tools used to estimate the cost of new light water reactors (LWRs). However, during the 1990s, the construction of new nuclear power plants in U.S. stopped, which resulted in the nuclear cost estimation tools, maintained by the U.S. Department of Energy (DOE), becoming outdated. A summary of these tools is presented in Section 5.

The purpose of this project was to develop and provide a cost estimation tool that can be used to determine the main cost drivers for new nuclear power plants. For each identified cost driver, a roadmap was developed to show the timeline over which technology would need to be developed and deployed to substantially reduce the cost of new plants. The cost estimation tool was then used to show the effect that example projects could have on reducing the Overnight Construction Cost (OCC) and the Levelized Cost of Electricity (LCOE).

In early 2000s, cost estimation methodologies and guidelines were developed by a number of organizations such as the Economics Modeling Working Group (EMWG) of the Gen IV International Forum. These methodologies were similar in structure to those that had been maintained by the DOE since the 1960's. Cost estimating studies were also undertaken by private companies, universities, and research organizations in anticipation of a nuclear renaissance in the 2010 timeframe. However, beginning in the early 2000's, the economics of nuclear power in Western countries became less favorable due to the availability of cheaper natural gas and the deployment of renewables, as an alternative for reducing the carbon footprint of electricity production.

Despite these factors, there is a continued interest in deploying new nuclear energy, but with the caveat that nuclear must be able to be deployed more economically. Nuclear has also a significant potential to take advantage of the economies of scale and is expected to decrease per-unit cost as more reactors are built (Ingersoll, 2019). Maintaining the nuclear industry's 20% market share of global energy production, will require adding ~60-90 GW (the nominal plant size assumed in this report was 1.1 GW) of new nuclear power, as shown in Figure 1-1. Being able to maintain the size of the current fleet is often seen as an important step in meeting future decarbonization targets.

Cost overruns and schedule delays experienced during recent nuclear projects and other large construction projects have contributed to skepticism regarding the economic feasibility of nuclear power. However, non-U.S. (including non-Western) regions that have committed to nuclear, have shown that with proper planning, execution, and application of novel technologies in some cases, the nuclear fleet can be expanded affordably. Analysis of recent nuclear projects has shown consistent similarities among successful projects and common challenges shared by projects that went over budget, did not meet construction schedule targets, or both. Some of these common traits are listed in Table 1-1.

The cost estimation tool built for this analysis, incorporates lessons learned from recent projects and can potentially help future owner-operators allocate their funding and invest in technologies that can substantially decrease the cost of new nuclear plants.

Table 1-1
Common Characteristics in Low and High Cost Nuclear Construction Projects (ETI, 2018 Appendix A)

Low Cost Plants	High Cost Plants
• Design at or near complete prior to construction • High degree of design reuse • Experienced construction management • Low cost and highly productive labour • Experienced EPC consortium • Experienced supply chain • Detailed construction planning prior to starting construction • Intentional new build programme focused on cost reduction and performance improvement • Multiple units at a single site • NOAK design	• Lack of completed design before construction started • Major regulatory interventions during construction • FOAK design • Litigation between project participants • Significant delays and rework required due to supply chain • Long construction schedule • Relatively higher labour rates and low productivity • Insufficient oversight by owner

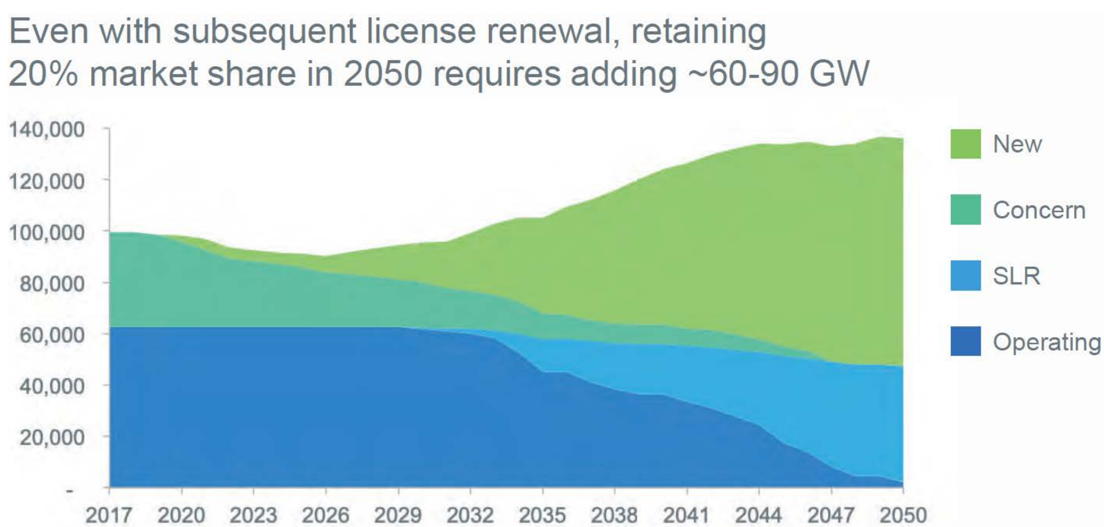

Figure 1-1
New Construction Needed to Maintain Nuclear's Current Market Share (NEI 2019 Appendix A)

2 SUMMARY AND ROADMAP

The following subsections provide the main conclusions of this modeling effort and lay out an example roadmap for addressing cost drivers for constructing nuclear power plants.

2.1 Summary

A deterministic bottom-up modeling approach (described in Section 6.2) was used to develop an AACE International Class 4/5 cost estimating analysis for “Nth of a Kind” (NOAK) LWRs. This analysis drew mainly from the DOE’s Energy Economic Database (EEDB) program developed in the 1970s and 1980s (discussed in Section 6.3). Consideration of cost reduction due to reduced construction schedule are included and based on G4ECONS model correlations (discussed in Section 6.4.12).

In parallel with model development, industry experts contributed ideas for cost drivers and what solutions might be used to address them. The resulting presentations and materials from the EPRI/GAIN/NEI co-sponsored workshop (held in Washington, D.C. on January 17-18) are documented in Appendix A of this report.

Although the codes of accounts are organized by components and grouped by direct and indirect costs, the surveyed industry experts phrased their cost drivers as concepts that extended across multiple Code of Accounts (COAs) with solutions that decreased costs in multiple ways (e.g., schedule reduction, increases to craft labor productivity, reductions in managerial labor expenses, lower material costs and quantities, etc.). To align with this approach, a set of twelve cost drivers were identified:

- Craft Labor Costs (Section 7.1.1)
- Baseline Civil/Structural Design Costs (Section 7.1.2)
- Baseline Constructability of Design (Section 7.1.3)
- Material Costs (Section 7.1.4)
- Inspection (QA/QC) Delays (Section 7.1.5)
- Reliance Upon Consensus Based Codes and Standards (Section 7.1.6)
- Excessive Margin (Section 7.1.7)
- Non-severability of Design Features (Section 7.1.8)
- Regulatory Requirements (Section 7.1.9)

- Supply Chain Issues (Section 7.1.10)
- Unknown Risks (Section 7.1.11)
- Workforce Training (Qualifications) (Section 7.1.12)

These cost drivers overlap in many cases (e.g., an increase in the constructability of a design may also contribute to a reduction in craft labor costs) and thus the sum total of the cost drivers adds up to more than $5500/kW (the baseline OCC). The magnitudes of five of these drivers (craft labor costs, civil/structural design, constructability of design, materials, and inspection QA/QC) were assessed as the other factors are qualitative in nature, in order to help focus research efforts towards addressing the most significant cost drivers.

The following conclusions can be drawn from this analysis:

- The cost of nuclear construction in the United States, adjusted for inflation, began increasing significantly following the Three Mile Island (TMI) incident and these cost increases promulgated through the last builds in the 1990s. Many organizations, states, utility commissions, and vendors tracked the costs over this timeframe and assembled very large and comprehensive databases of costs through the early 2000s. While a number of the $5500/kW baseline OCC starting points were considered for this project (EIA data, published EPC estimates, predictions generated by universities and research organization, analyses by financial institutions, EPRI findings, etc.), the project chose to start from the most recent data produced by the U.S. DOE under the EEDB program (the so-called 1987 “Phase IX Update” to the 23-year study sponsored by DOE). More specifically, the baseline PWR12ME (or median estimate) costs, labor hours, materials and commodity costs, and schedule data from 1987 were adjusted for inflation to 2017. This resulted in an extrapolated predicted OCC of $5500/kWe.
- The consensus reached by the industry experts engaged as part of this project, was that if a notional $3000/kWe OCC could be achieved, nuclear would likely be a financially attractive source of electricity, although it would still be significantly more expensive per kWe than most other energy technologies in many parts of the United States. The main conclusion from the comparison above is that extrapolating U.S. experience/construction experience and performance from the late 1980’s to today would not lead to meeting target goals for costs.
- Consistent with the findings of other studies, the direct cost of the nuclear island was found to be less than 20% of all direct costs (i.e., 80% of on-site labor, on-site materials, and off-site manufacturing are for components in the balance of plant). Therefore, the perception that only the NSSS reactor hardware cost that must come down to make nuclear competitive, is not correct; significant savings should also be pursued in the balance of plant.
- Reducing the construction time from 72 months (nominal case cited by the EEDB for PWR12 “Better Experience” or PWR12 BE) to 55 months results in a reduction in indirect costs of $456/kW (according to the methodology described in Section 6.4.12). Reductions in schedule also significantly decrease the risk and the cost of schedule delays.
- Many cost overruns during plant construction occur because the FOAK plant designs are not 100% completed prior to the beginning of construction. There is a strong negative correlation between percent design completion and OCC.

- Labor cost was determined to be the largest cost driver in building a Pressurized Water Reactor (PWR) in the U.S. such as the IPWR12 design described in detail in the EEDB program. Labor accounted for $2925/kWe of the $5500/kWe projected cost or over 50% of OCC. The two contributors to total labor costs were direct labor ($982/kW or 18% of total cost) and labor associated with indirect costs (i.e., professional services, home office engineering, etc. $1943/kW or 35% of total cost). In this project, it was shown that increasing worker productivity is a key opportunity in that it not only decreases craft labor costs (payroll per amount of work completed), but it also significantly reduces schedule, resulting in savings across multiple fronts. An additional opportunity is to reduce the number of indirect labor hours (see later sections of this report for a breakdown of various “code of accounts” (COA) that tabulate labor hours for dozens of construction and indirect cost activities).
- It was estimated that the lack of constructability affects $2338/kW of total OCC. Roughly half of this is structures and improvements, while the other half is distributed across other COAs. In 1987, DOE examined opportunities for improved constructability in a hypothetical design called the IPWR12 (Improved PWR12). The IPWR12 model predicts that better design and construction methods could decrease these applicable “code of accounts” or COAs by 15-35% which equates to $503/kWe or about 20% of the target cost reductions needed to reach the notional $3000/kWe goal, to make nuclear more competitive with fossil plants.
- Civil and structural design was also found to be a significant cost driver, largely because any advancements in this area have the potential to decrease the construction duration (and indirect costs), as modularization allows construction activities to be conducted in parallel. As with many of the other cost drivers, over half of the potential cost savings ($456/kWe out of $892/kWe) in this cost driver are a result of schedule reduction.
- The cost of materials is often perceived to be a major cost driver. However, the results show that reducing the cost of all plant materials by 50% would only result in $343/kWe of savings ($258/kWe in materials and $125/kWe in indirect costs). Technologies that save materials should be identified, but particular focus should be placed on identifying building materials that facilitate construction (e.g., materials that reduce construction duration or inspection requirements).
- Inspection delays are one of the identified reasons that contributes to reduced worker productivity in nuclear construction. Proper training of inspectors could reduce inspection delays resulting in reductions in labor costs. Additional savings could be realized if reductions in inspection time resulted in reduced indirect costs.

The most significant cost reduction strategies are those that are able to reduce construction duration, in addition to the savings in labor and to a lesser extent, the savings in materials. These savings are further amplified when accounting for reduced interest costs.

Section 7.3 shows that technology areas are likely to have a larger effect if they meet some or all of the following criteria: decrease interference between resources, reduce project timeline, affect multiple cost drivers, and affect multiple components.

If existing technologies are used to improve all five of the quantitatively assessed cost drivers, **there is an opportunity to reduce costs by $2079/kW from the existing baseline OCC of $5500/kW**, resulting in a potential OCC cost of $3421/kW.

For LCOE, an estimate of potential reductions can be made by assuming OCC represents about 60% of the $88/MWh baseline LCOE value. More details are presented in Section 7.2.5 of this report.

Additional cost reductions could also be made by addressing any cost drivers for which a quantitative analysis was not done (quantitative analyses were performed only for the five drivers deemed quantitative in nature, i.e., craft labor, civil/structural design, constructability of design, materials, and inspection QA/QC), or assuming more aggressive cost reductions for the analyzed cost-drivers, or assuming larger reductions in schedule.

2.2 Roadmap

The following tables present notional roadmaps for the EPRI Advanced Nuclear Technology (ANT) program to optimize the potential impacts and benefits, and also to suggest possible directions for research programs at other organizations (such as DOE), advanced reactor vendors, national laboratories, and universities. Each roadmap includes potential solutions that could be investigated to address the cost drivers discussed in Section 7.1 and 7.2. A short summary of each driver is provided below.

- Constructability of Design (Table 2-1 and Section 7.1.3) – The constructability of a design is the degree to which obstacles faced during construction are foreseen and avoided during the design phase. The cost of construction is reduced by designing structures that are easier to build.
- Civil/Structural Design (Table 2-2 and Section 7.1.2) – The civil/structural components of nuclear power plants are some of the largest in the world. Proper application of modularity, increased use of factory fabrication, and some advanced building technologies such as steel-plate composites or use of ultra-high performing concrete can significantly reduce the cost of these components.
- Materials of Construction (Table 2-3 and Section 7.1.4) – The cost of materials is the purchase price of the materials required for construction. This cost can be reduced by technologies that allow substitution of less costly material or decreased quantities of the materials used.
- Craft Labor Cost (Table 2-4 and Section 7.1.1) – The cost of on-site labor (also referred to as craft labor, to be able to distinguish it from indirect labor) can be decreased through efforts made to increase the productivity of the workers on site.
- Inspection (QA/QC) (Table 2-5 and Section 7.1.5) – QA inspections during/after components are completed take significant time and can lower productivity (e.g., workers waiting for inspections to be completed). There are numerous ways in which these inspections could be made faster or even eliminated.

The magnitude of these cost drivers was determined using the cost estimating tool. These results are shown in Section 7.2.

There are various organizations with strengths that make them well suited to pursue different kinds of projects to address the cost drivers identified in this study and reported herein. The research documented in this report highlights the collaboration needed to implement concepts that begin as research projects. Each timeline provides research areas that could be investigated in the 2020-2021 timeframe. The goal of this research would be for vendor trials to begin in 2022 so that in 2023 and beyond the technology could be implemented by design engineers and construction workers. Differences in the maturity of various technologies will increase or reduce the time required for each phase. Research into additional areas should be pursued as funds are available.

Part of the scoping research in each phase should include utilization of the cost estimating tool to determine the potential effect for each solution (see Section 7.3). For each of the cost drivers below, some potential solutions have been listed. These solutions were identified at EPRI meetings (EPRI 2018a Appendix B and EPRI 2019 Appendix A). These are examples of the kind of technologies and methodologies that should be considered for each cost driver.

Table 2-1
Constructability of Design Roadmap

Technical Topic	Owner*	2020	2021	2022	2023 and Beyond
Constructability of Design $503/kW savings available	EPRI	Scoping Research	Identify opportunities to separate the nuclear island from the balance of plant.	Vendor Trial Implementation	
			Investigate use of artificial intelligence (AI) for a bottom-up design.		
	Vendors				Field Implementation
	Purchasers	Complete plant designs so they are 100% designed before the next project breaks ground.			
	Other Organizations		Investigate Building Information Modeling (BIM) standards used in Europe and create a similar system for the United States.		

*This designation is not meant to exclude other organizations from working on projects suggested for EPRI or vice versa, it is meant to highlight the collaboration needed to implement concepts that begin as research projects.

Table 2-2
Civil/Structural Design Roadmap

Technical Topic	Owner*	2020	2021	2022	2023 and Beyond
Civil/Structural Design $892/kW savings available	EPRI	Scoping Research	Identify additional opportunities to fabricate components off-site (increase modularity).	Vendor Trial Implementation	
			Evaluate lessons learned from modular construction projects world-wide.		
	Vendors				Field Implementation
	Purchasers				
	Other Organizations		Increase appropriate use of seismic isolation.		

*This designation is not meant to exclude other organizations from working on projects suggested for EPRI or vice versa, it is meant to highlight the collaboration needed to implement concepts that begin as research projects.

Table 2-3
Materials of Construction Roadmap

Technical Topic	Owner*	2020	2021	2022	2023 and Beyond
Materials of Construction $383/kW savings available	EPRI	Scoping Research	Estimate benefits of high strength rebar.	Vendor Trial Implementation	
			Develop smart formwork for concrete.		
	Vendors	Develop manufacturing processes for new materials of construction			Field Implementation
	Purchasers	Evaluate existing advanced materials and determine their suitability.			
	Other Organizations		Develop method for testing concrete prior to transport to pour site.		

*This designation is not meant to exclude other organizations from working on projects suggested for EPRI or vice versa, it is meant to highlight the collaboration needed to implement concepts that begin as research projects.

Table 2-4
Craft Labor Cost Roadmap

Technical Topic	Owner*	2020	2021	2022	2023 and Beyond
Craft Labor Cost $948/kW savings available	EPRI	Scoping Research	Assess more rigorous planning processes (e.g., Last Planner System [LPS])	Vendor Trial Implementation	
			Assess lean operating principles that rely on a holistic approach instead of traditional command and control processes.		
	Vendors				Field Implementation
	Purchasers	Implementation of electronic work packages, workforce training, training sessions for project managers.			
	Other Organizations		Evaluate alternate contractual frameworks.		

*This designation is not meant to exclude other organizations from working on projects suggested for EPRI or vice versa, it is meant to highlight the collaboration needed to implement concepts that begin as research projects.

Table 2-5
Inspection (QA/QC) Roadmap

<table>
<tr><th>Technical Topic</th><th>Owner*</th><th>2020</th><th>2021</th><th>2022</th><th>2023 and Beyond</th></tr>
<tr><td rowspan="5">Inspection (QA/QC) $151/kW savings available</td><td rowspan="2">EPRI</td><td rowspan="2">Scoping Research</td><td>Automate the inspection and qualification of concrete.</td><td rowspan="3">Vendor Trial Implementation</td><td rowspan="2"></td></tr>
<tr><td>Develop continual or near-real-time inspections of material and member placement (deployment can be through laser, drone, scanner, etc.)</td></tr>
<tr><td>Vendors</td><td></td><td></td><td rowspan="2">Field Implementation</td></tr>
<tr><td>Purchasers</td><td></td><td>Develop rationale for fewer inspections (leverage risk-informed strategies for reducing inspections).</td><td></td></tr>
<tr><td>Other Organizations</td><td></td><td></td><td></td><td></td></tr>
</table>

*This designation is not meant to exclude other organizations from working on projects suggested for EPRI or vice versa, it is meant to highlight the collaboration needed to implement concepts that begin as research projects.

3
NUCLEAR COSTS AND FIGURES OF MERIT

In order to accurately assess the costs of a nuclear power construction project and compare them to other energy generation technologies, it is important to clearly define the metrics used to express the cost of construction projects. These metrics are hereby referred to as figures of merit (FOMs). The FOMs used in this report rely on assumptions about capital costs, indirect costs, operating costs, and operating revenue. When making comparisons about the costs of various technologies, assumptions about these values are consistent unless otherwise stated. The following sections define the FOMs used herein.

3.1 Base Cost (BC)

Base cost (BC), which is defined as the sum of direct and indirect costs, is discussed in some of the references and also shown in Figure 3-1.

$$BC = Direct\ Costs + IndirectCosts$$ **Equation 3-1**

Direct costs are sometimes assumed to be only the *equipment cost*, but they also include the factory equipment costs (the turbine, etc.), the site labor required to install the equipment, and the site materials costs (formwork, scaffolding, raw materials, etc.). Indirect costs are largely constructions services, engineering and home office services, and field supervision required for the overall project execution, but not assignable to any one piece of equipment.

3.2 Overnight Construction Costs (OCC)

OCC is the cost of construction if all capital costs were incurred at once (hence the term "overnight"). This metric does not involve interest payments. The University of Chicago (2004) notes that the U.S. definition of OCC includes contingency costs and owner's costs although there are some notable references (for example IAEA 2000 and NEA 1998) that count these factors separately. OCC is given by the following formula:

$$OCC = Direct\ Costs + Indirect\ Costs + Contingency\ Costs + Owner's\ Costs$$ **Equation 3-2**

OCC are expected to be roughly 60% of the levelized cost of electricity (see Section 3.4 for a discussion of LCOE) (Ganda et al. 2018). OCC, sometimes also called Overnight Cost (OC), is shown in Figure 3-1. Some references include the cost of the first fuel load in OCC (i.e., working capital), however this inclusion is not consistent.

A subtle point to remember is that OCCs are not truly schedule independent. The planned construction schedule inherently includes OCC items that are construction-time dependent, such as indirect costs, warehousing, home office staff, engineering staff. Any delays in schedule, not only affect the interest costs during construction financing, but also the final OCC achieved.

3.3 Total Capital Investment Cost (TCIC)

Total Capital Investment Cost (TCIC) is the sum of direct costs and indirect costs, escalation, interest during construction (IDC), and owner's cost. These are the costs incurred throughout a project schedule up until the plant begins operation and begins producing revenue. TCIC is shown in Figure 3-1.

$$\begin{aligned} TCIC = &\ Direct\ Costs + Indirect\ Costs + Contingency\ Costs \\ &+ Owners\ Costs + Escalation \\ &+ Interest\ During\ Construction \end{aligned} \quad \textbf{Equation 3-3}$$

3.4 Levelized Cost of Electricity (LCOE)

The LCOE is a metric used to combine capital cost (*C*), operating and maintenance costs (*O*), and the cost of fuel (C_f). Equation 3-4 shows these terms together. This equation is visualized with Figure 3-1. It factors in the major costs of electricity production over the lifetime of the plant and coverts them to one-time weighted number which is normalized by the sum of the electrical energy produced over time (Champlin 2018). Using LCOE for cost comparisons allows plant owners to accurately assess the return on the initial capital investments.

$$LCOE = \frac{1000}{8766 * L}\left[\Phi\frac{C}{\eta K_{th}} + \frac{O}{\eta K_{th}}\right] + 1000\frac{C_f}{24\eta B} \quad \left[\frac{\$}{MWhre}\right] \quad \textbf{Equation 3-4}$$

$$\Phi = \frac{[x(1+x)^N] \big/ [(1+x)^N - 1]}{1-\tau} - \frac{\tau}{N(1-\tau)} \quad \textbf{Equation 3-5}$$

$$x = \frac{E}{E+D}R_E + \frac{D}{E+D}R_D(1-\tau) \quad \textbf{Equation 3-6}$$

Where:

- L Capacity Factor
- Φ Levelized Fixed Charge Rate (1/yr)
- C Total Capital Cost
- O Annual Operating & Maintenance Cost ($/yr)
- η Thermodynamic Efficiency

K_{th} Plant Thermal Power (MWth)

C_f Fuel Cycle Cost ($/kg)

B Burnup at Discharge (MWthD/MTU)

x Discount Rate

N Economic Plant Life (yrs)

τ Composite Tax Rate

E Total Equity

R_E Cost of Equity ($)

D Total Debt

R_D Cost of Debt ($)

Sometimes LCOE is also referred to as Levelized Unit Electricity Cost (LUEC), Long Run Average Cost (LRAC), Levelized Unit Power or Production Cost (LUPC), Levelized Discounted Electricity Generation Costs (LDEGC), or Levelized Cost (LC).

Interest during construction (IDC), which is the amount of interest disbursed as interest payments on borrowed capital during construction, is included in LCOE but not OCC.

Owner's Costs are the costs borne by owner, and they are associated with the construction but are not part of the base construction, supplementary, or finance costs. These include, but not limited, the cost of land, project oversight, operator training, system activities, license fees, and taxes.

Deactivation and decommissioning (D&D) costs may be added to the LCOE, but this analysis excludes it on the assumption of separate financing, such as government or corporate contributions.

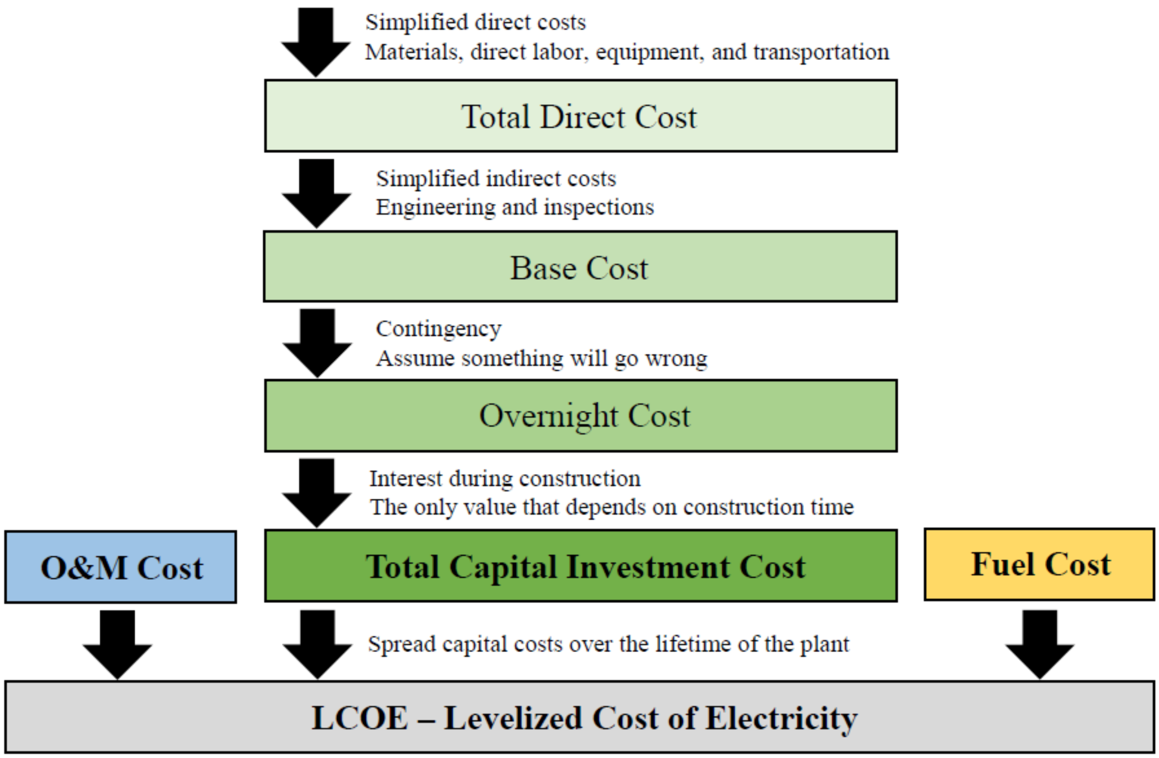

Figure 3-1
Graded Line Item Costs of Figures of Merit that Affect LCOE. Figure Courtesy of MIT. (Champlin 2018)

3.5 Other Excluded Figures of Merit

There are some references that use other FOMs, but they are not discussed in this report. Often, the other FOMs are derivatives of the four terms listed above. As was stated with OCC, when comparing figures from one reference to another, it's necessary to identify the underlying assumptions. The reason for this is because the calculation of these figures is not consistent among references or, sometimes, even among different editions of the same reference.

4
HISTORICAL TRENDS

EPRI's 2009 report, *The Power to Reduce CO_2 Emissions: The Full Portfolio: 2009 Technical Report* (EPRI 2009) predicted a massive increase in the production of nuclear power through 2050. This scenario was envisioned prior to the advances in natural gas production (e.g., hydrofracking, horizontal drilling) that have redefined the last decade of energy production in the United States. Looking forward, there are numerous economic and policy factors that could significantly change the industry outlook and there is also a possibility for a scenario in this the natural gas production could dramatically fall off. A focus on carbon-free technologies could force fossil plants to pay a carbon tax or build carbon capture and storage systems (CCS). Even in a world without these dramatic shifts, EPRI's U.S. Regional Economy, Greenhouse Gas, and Energy (US-REGEN) model predict that nuclear has a role to play (EPRI 2018b). In case this scenario comes to fruition, the nuclear industry should be positioned well, so that it will be a financially attractive resource for generating electricity and energy.

The investment in nuclear over the next half century will be driven by the expected capital cost of new reactors as well as the perceived public risk[1]. The IPWR12 model adjusted for inflation predicts an OCC of $5500/kWe. Figure 4-1 shows the share of worldwide energy production projected for various energy technologies given different target LCOEs. In scenarios where LCOE is not decreased, models predict a decrease in nuclear market share. Figure 4-2 shows similar analysis results in terms of total new capacity.

The accident at Three Mile Island (TMI) Unit 2 lead to increased oversight from the NRC and a corresponding jump in both the overnight construction cost and construction duration of new nuclear plants in the United States (Lovering et al. 2016). Table 4-1 shows that prior to the accident at TMI, power plant construction took an average of 5.6 years and had an average OCC of 1350 $/kWe[2] as completed (Lovering et al. 2016). This is shown graphically in Figure 4-3.

An extensive study of the nuclear power plants (NPP) cost growth showed that 75% of cost increases between pre- and post-TMI plants, could be attributed to the increased base costs while the rest of the increase (25%) was related to financing. Of all the factors examined, construction duration was the factor most closely correlated with OCC (Lovering et al. 2016). This relationship is illustrated by Figure 4-3.

There is a slight positive correlation between plant capacity and OCC. A 25% increase in capacity leads to an 18% increase in construction duration, which results in a 22% increase in OCC (U.S. EIA 2016).

[1] Addressing public perception of the industry is beyond the scope of this effort.

[2] In 2018 dollars

Utilities that acted as their own construction managers had OCC values roughly 35% lower than those that contracted out these duties (Gillespie et al. 2016).

Due to the differences in the approach each country used in building their nuclear plant fleets, there are a variety of trends that correlate OCC and construction start dates (Figure 4-4). While the United States has seen an increase in OCC over time (Figure 4-3), South Korea has seen a significant decrease (Figure 4-5) (Lovering et al. 2016). This cost decrease can generally be attributed to: (1) Nth of a kind (NOAK) savings which were realized because of design consistencies across the entire fleet, (2) a mature supply chain, and (3) a continuous build order book and experienced project management and craft.

Table 4-2 shows a comparison of OCC nuclear and alternative technologies published by MIT. Interestingly, the “nuclear premium” between nuclear and combined cycle gas turbine (CCGT) is almost identical between the U.S. and China (5.8x vs. 5.6x, respectively, for the nominal cases).

The first commercial nuclear power plants were built over 60 years ago, and since then, the regulatory requirements have increased project scope. Although the situation is unique for each country and regulatory environment, there would be substantial value in finding ways for OCC to return to pre-TMI levels.

Table 4-1
Early Projects had Short Construction Times and Limited Cost Overruns (Ganda 2019 Appendix A)

Unit	Output (MW)	Type	State	Construction Start	Construction End	Construction Duration (years)	Lifetime (years)	Thermal Efficiency (%)	OCC (2018 $/Kw)	Total Capital Cost (2018 $/Kw)
Palisades	697	PWR	MI	3/15/1967	12/31/1971	4.8	40	32.90	889.76	998.3
Vermont Yankee	507	BWR	VT	12/12/1967	11/30/1972	5	40	33.70	1857.24	2091.74
Maine Yankee	879	PWR	ME	10/22/1968	6/29/1973	4.7	23.4	32.50	1425.76	1591.92
Pilgrim	672	BWR	MA	8/27/1968	12/2/1972	4.3	40	33.50	1823.74	2011.34
Surry 1	790	PWR	VA	6/26/1968	12/22/1972	4.5	40	33.90	1180.54	1310.52
Turkey Point 3	672	PWR	FL	4/28/1967	12/14/1972	5.6	40	31.00	765.14	879.04
Surry 2	793	PWR	VA	6/26/1968	5/1/1973	4.8	40	33.90	1180.54	1325.26
Oconee 1	851	PWR	SC	11/7/1967	7/15/1973	5.7	40	32.80	818.74	943.36
Turkey Point 4	673	PWR	FL	4/28/1967	9/2/1973	6.4	40	31.00	765.14	899.14
Prairie Island 1	511	PWR	MN	6/26/1968	12/16/1973	5.5	40	31.80	1811.68	2071.64
Zion 1	1069	PWR	IL	12/27/1968	10/19/1973	4.8	23.3	32.50	1222.08	1370.82
Fort Calhoun	478	PWR	NE	6/8/1968	9/26/1973	5.3	40	32.10	1922.9	2186.88
Kewaunee	521	PWR	WI	8/7/1968	6/16/1974	5.9	40	31.00	1687.06	1952.38
Cooper	764	BWR	NE	6/6/1968	7/2/1974	6.1	40	31.80	1606.66	1871.98
Peach Bottom 2	1078	BWR	PA	2/1/1968	7/2/1974	6.4	40	32.40	1618.72	1905.48
Browns Ferry 1	1026	BWR	AL	5/11/1967	7/31/1974	7.2	11.4	32.70	1072	1294.44
Oconee 2	851	PWR	SC	11/7/1967	9/9/1974	6.8	40	33.10	818.74	976.86
Three Mile Island 1	790	PWR	PA	5/19/1968	9/2/1974	6.3	40	30.60	2115.86	2481.68
Zion 2	1001	PWR	IL	12/27/1968	11/14/1973	4.9	22.8	32.50	1222.08	1373.5
Arkansas 1	836	PWR	AR	12/7/1968	12/19/1974	6	40	30.80	1192.6	1388.24

Table 4-2
Overnight Construction Costs for Nuclear and Alternative Technologies. Data provided courtesy of MIT. (Champlin 2018)

	Cost ($/kW)	OCGT	CCGT	Coal IGCC	Nuclear	Wind	Solar	Battery Storage	Coal IGCC+CCS	Gas CCGT+CCS
United States	Low				4,100	1,369	551	429		
	Nominal	805	948	3,515	5,500	1,553	917	715	5,876	1,720
	High				6,900	1,714	1,898	1,430		2,215
China	Low				2,094	1,117	404	429		
	Nominal	421	496	1,160	2,796	1,267	671	715	1,940	900
	High					1,398	1,389	1,430		1,159
United Kingdom	Low Cost				6,070	1,887	484	429		
	Nominal	865	953	3,515	8,142	2,142	804	715	5,875	1,434
	High					2,363	1,665	1,430		1,847
France	Low				5,067	1,511	481	429		
	Nominal	890	980	3,515	6,797	1,715	801	715	5,876	1,475
	High				8,496	1,892	1,657	1,430		1,899

Assumed LCOEs for different technologies, based on nominal U.S. costs, were as follows: wind – $72/MWh; solar – $99/MWh; nuclear – $97/MWh; CCGT-CCS – $90/MWh; OCGT – $87/MWh; CCGT – $64/MWh; IGCC – $77/MWh; IGCC-CCS – $125/MWh. Note that these LCOEs assume U.S. Energy Information Administration capacity factors of 34% for wind and 25% for solar.

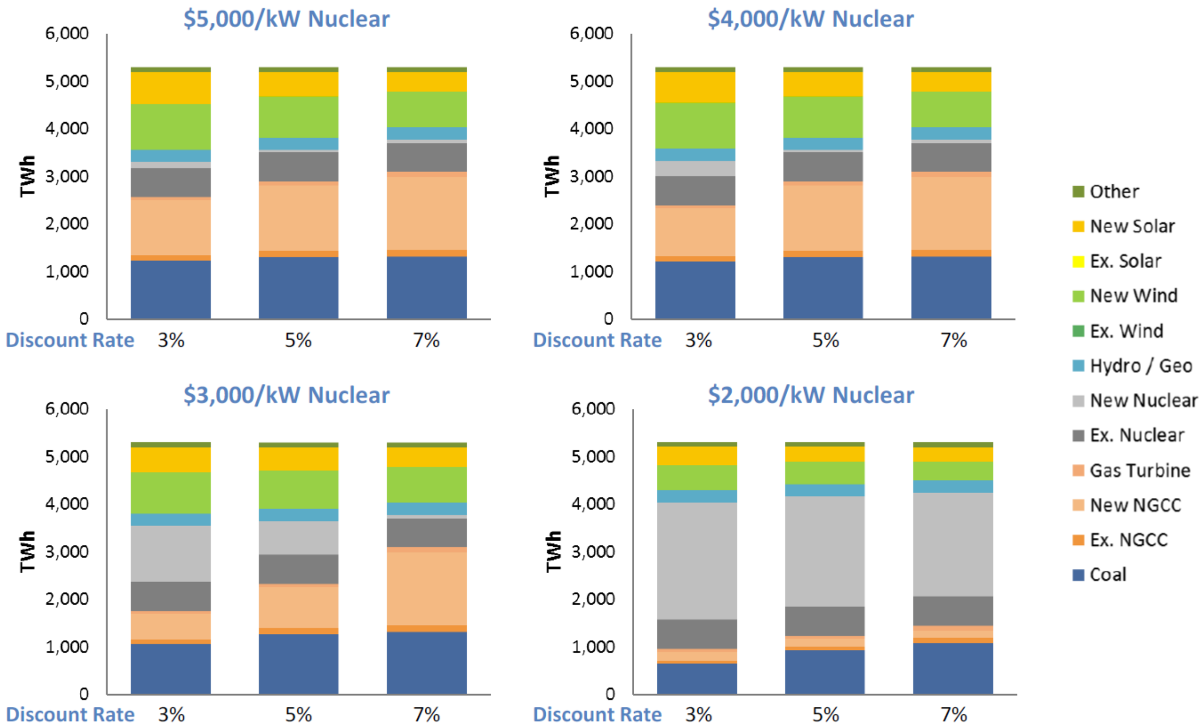

Figure 4-1
Sensitivity of the Electric Generation Mix in 2050 by Technology Across Different Discount Rates (Bars) and Nuclear Capital Costs (Panels) (EPRI 2018b)

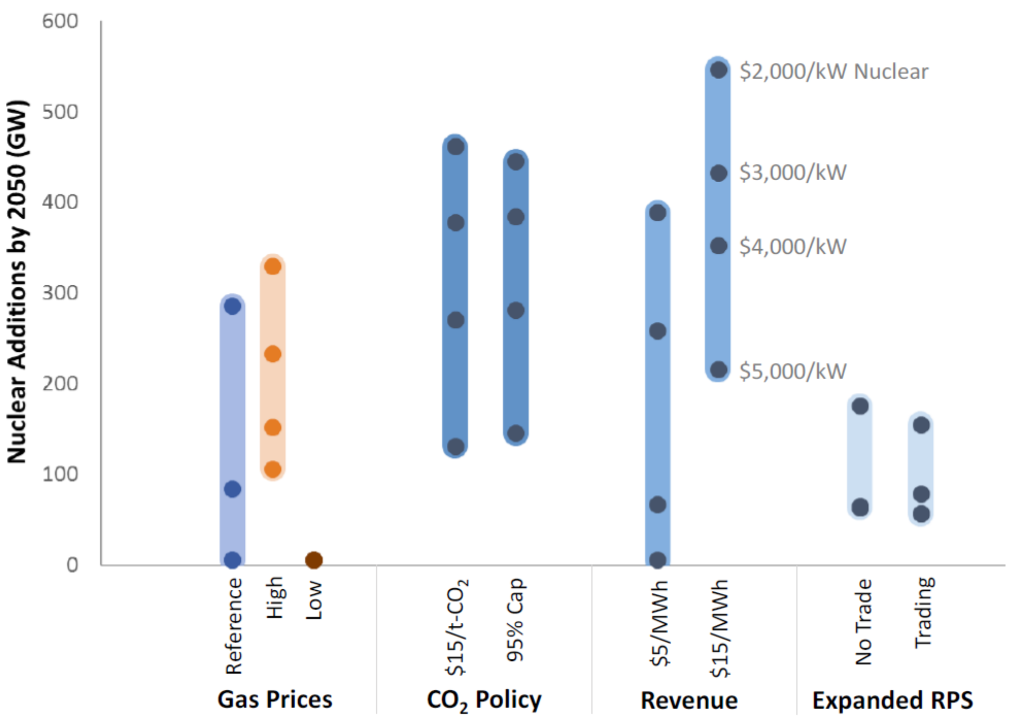

Figure 4-2
Cumulative Nuclear Additions Through 2050 (GW) Across all Sensitivities (EPRI 2018b)

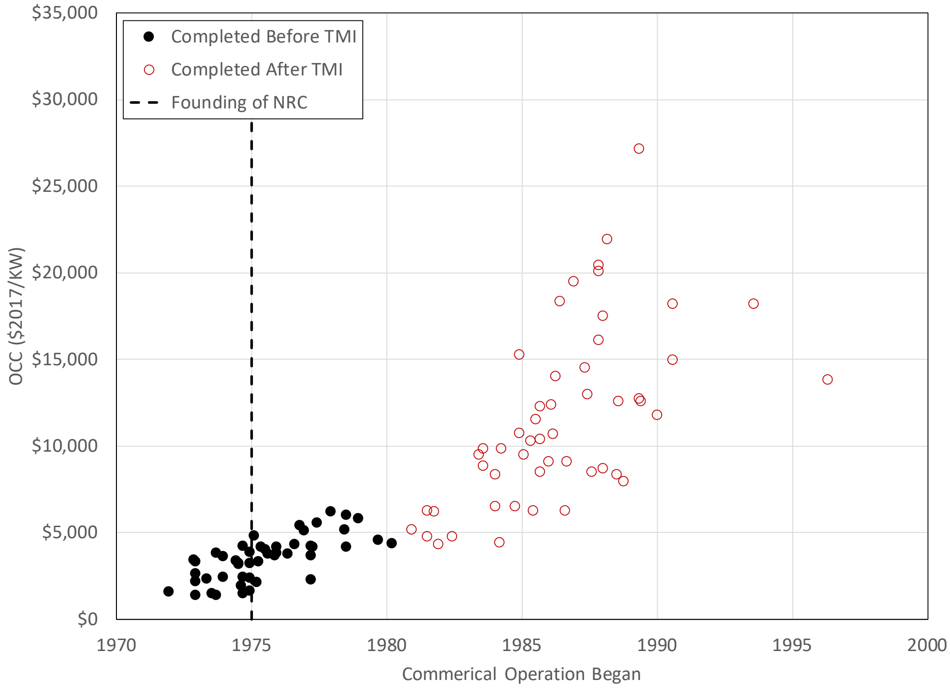

Figure 4-3
Overnight Construction Cost as a Function of Construction Duration (Data from Lovering et al. 2016)

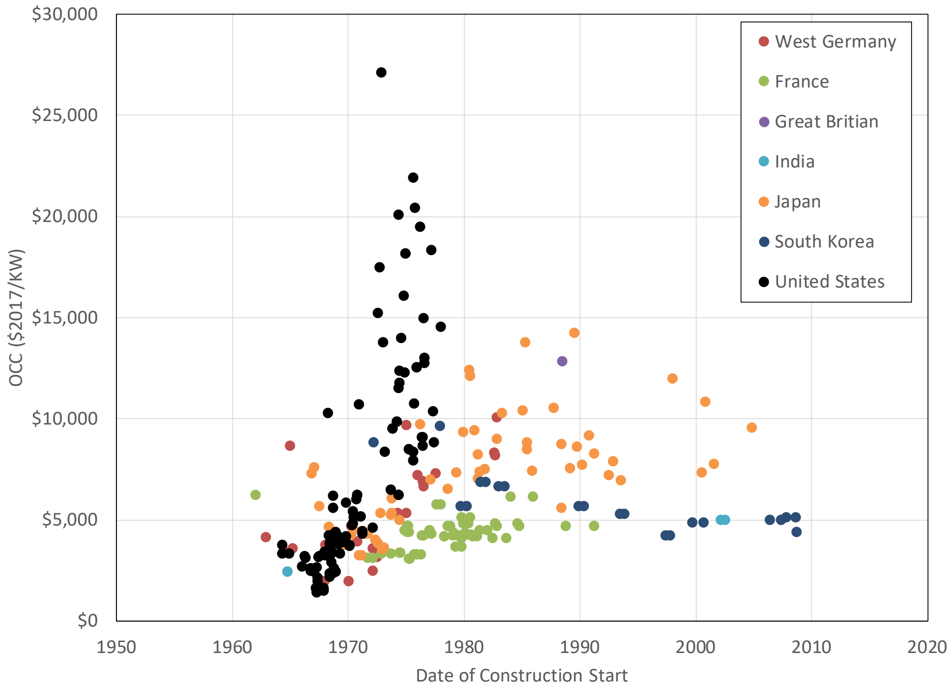

Figure 4-4
Relationship Between OCC and Construction Start World Wide (Data from Lovering et al. 2016)

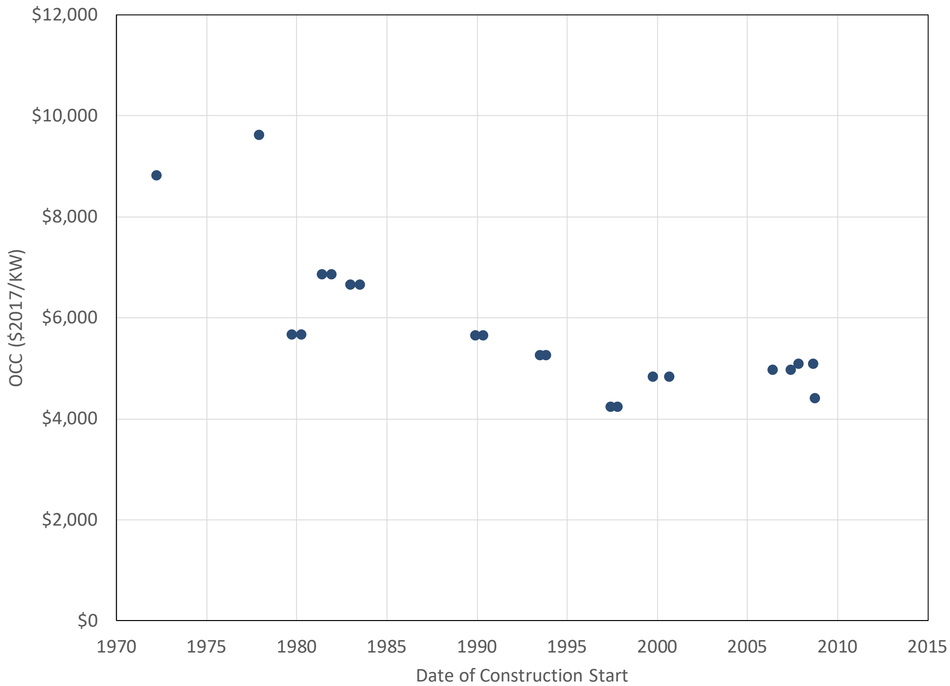

Figure 4-5
OCC as a Function of Construction Start Date for Korean Nuclear Projects (Data from Lovering et al. 2016)

5
NOTABLE COST STUDIES

In total, 20 models and approximately 100 associated references were reviewed when compiling this report. From these, 11 models were down selected for comparison and are listed in Table 5-1. Each of these studies present different treatments of indirect costs, owner's costs, non-recurring engineering (NRE) costs, first of a kind (FOAK) costs versus N^{th} of a kind (NOAK) savings, and fuel cycle costs. Figure 5-1 shows a timeline of when these studies were published.

The Energy Economic Database (EEDB) resulted from a project with the expressed purpose of estimating the cost of nuclear power generation and comparing that cost to other technologies (e.g., coal fired power plants). The work on this project began with Atomic Energy Commission (AEC) sponsorship in 1960s. The first edition was published in 1978 and nine more revisions were published, with the ninth revision released in 1988. All told, the project covered 33 plant configurations, eight of which were nuclear. The code of accounts listed in the EEDB (and further discussed in Section 6.3) provides estimates of the materials and labor needed to produce over 400 subsystems and groups, organized into over 50 major groups (there are over 10,000 total inputs to the model). The EEDB does not provide cost estimates for contingency, IDC, or escalation. Furthermore, it is generally considered non-conservative with respect to training facilities, end of cycle (EOC), security (estimates do not account for post 9/11 requirements), IT systems, and QA/QC. EEDB is considered overly conservative with respect to office space.

The model developed for this analysis draws most significantly from the EEDB, but the others were used as references to evaluate historical trends discussed in Section 4 and the assumptions discussed in Section 6.4.

Table 5-1
Description of Notable Cost Studies

		1	2	3	4	5	6
	Organization	**DOE**	**OECD**	**ORNL**	**IAEA**	**U Chicago**	**B&V**
	Name	EEDB	G4ECONS	Guidelines	396	EPIC	Cost Report
	Year(s)	1978-1988	2000-2007	1993	2000	2004/2011	2012
Revisions/ Updates		9	Several			1	
Plant Designs	PWR	•	•	•	•	•	•
	BWR	•	•	•	•	•	•
	PHWR	•	•	•	•		•
	Advanced Nuclear	•	•	•			
	Fossil	•		•			•
	Total Number	33	>6	>6	Guideline	5	15
Maturity	Existing	•	•	•	•	•	•
	Future	•	•	•			
Methodology	Bottom-Up	•	•		•	•	•
	Top-Down						
Siting		Generic	Specific	Generic	Specific	Specific	Generic
Analysis	OCC	•	•	•	•	•	•
	DC	•	•	•	•	•	•
	Indirect Costs	•	•	•	•	•	
	Labor-hours	•	•	•			
	Owners Cost		•	•	•	•	•
	TCIC		•	•	•	•	•
	LCOE (LUEC)		•	•	•		
	IDC		•	•	•		
	Fuel Cycle		•	•	•		
COA	Yes/No	Yes	Yes	Yes	Yes	Yes	Proprietary
	n-Digit	Up to 9	3-6	Up to 6	2 to 3	2	Unknown
Data Source	Experience	•	•	•	•	•	•
	Public	•	•	•	•	•	
	Engineering	•	•	•			
	Utility	•	•	•		•	
	Vendor	•	•	•			
	Expert Elicitation	•	•			•	
	Proprietary	•	User Input				•
Schedule Analysis		Limited	User Input	User Input			•

Table 5-1
Description of Notable Cost Studies (continued)

		7	8	9	10	11
	Organization	**Breakthrough (Lovering)**	**EON**	**Cleantech**	**ANL (Ganda)**	**OECD**
	Name	EP	EIRP	ETI	ICAAP	Reduced Cap
	Year(s)	2016	2017	2018	2016	2000
Revisions/ Updates						
Plant Designs	PWR			•	•	•
	BWR				•	•
	PHWR					•
	Advanced Nuclear		•	•		•
	Fossil					
	Total Number	349	8	33	4	>18
Maturity	Existing			•	•	•
	Future		•	•		
Methodology	Bottom-Up			•		•
	Top-Down			•		•
Siting		Specific	Generic	Specific	Generic	Specific
Analysis	OCC	•	•	•	•	•
	DC	•	•	•	•	•
	Indirect Costs		•	•	•	•
	Labor-hours		•			
	Owners Cost			•	•	•
	TCIC		•	•		
	LCOE (LUEC)		•	•	•	
	IDC		•	•	•	
	Fuel Cycle					
COA	Yes/No	No	Yes	Yes	Yes	Yes
	n-Digit		3	3	3	2
Data Source	Experience			•	•	•
	Public	•		•	•	•
	Engineering					•
	Utility	•		•	•	•
	Vendor		•			•
	Expert Elicitation			•		•
	Proprietary		•			
Schedule Analysis						

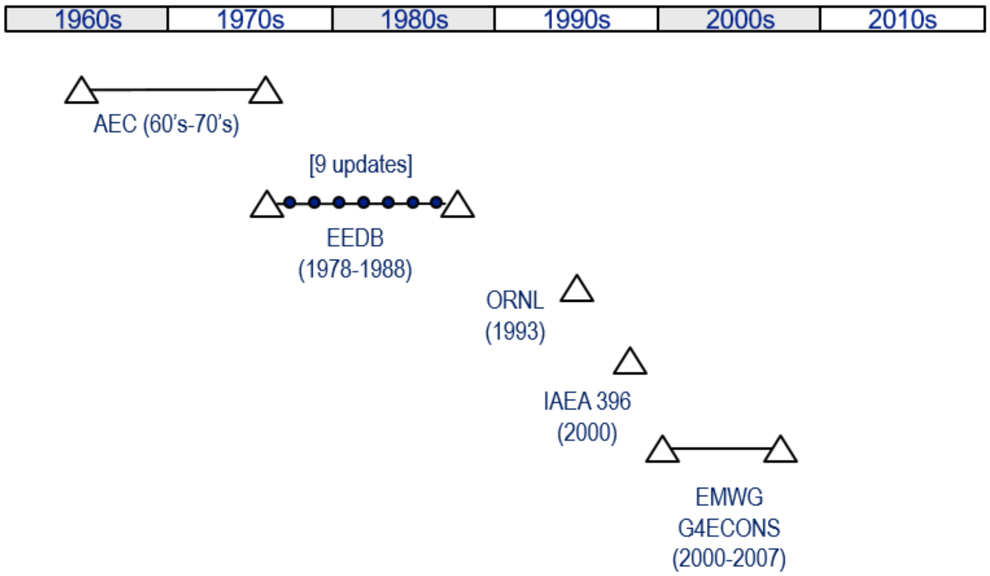

Figure 5-1
Timeline of Notable Cost Studies

6
MODELING INPUTS

To support this project, a model was developed to evaluate the effect of R&D initiatives on cost reductions on the FOMs. Although cost studies (particularly early stage) have historically been inaccurate in predicting final cost and schedule for large construction projects (including nuclear plants), an examination of recent operating experience highlights a number of common factors that lead to model inaccuracy (e.g., design changes, regulation, supply chain challenges, low productivity).

It is noted that these cost drivers will be more significant for FOAK designs. Due to this risk, there is a possibility that this model is not more effective than the rest, regarding the estimation of the cost for particular nuclear projects. However, the improved granularity of these cost predictions provides a framework with which the key cost drivers for LWRs can be assessed. Some of these cost drivers were identified in the cited references, some through discussions with industry experts (EPRI 2018a Appendix B and EPRI 2019 Appendix A), or through modeling. Although the specific COA for other reactor designs are different and the magnitude of each cost driver is design-specific, due to design similarities, similar cost drivers are expected to applicable to those designs.

6.1 How to Use This Model

The magnitude of the cost drivers was determined first by identifying which COAs were affected by the driver. For each COA, a percentage was assigned (% affected by cost driver) to show if the COA applies to the entire cost driver (100%) or just a fraction. Multiplying the baseline cost for each COA by the assigned percentage affected results in the baseline cost contribution. The sum of these shows the magnitude of the cost driver. Then, a "% reduction from baseline contribution" was determined to show what reasonable fraction of the cost driver can be could be eliminated through advancements in technology (or deployment of existing technology). The potential cost savings is the baseline cost contribution multiplied by the percent reduction.

This same methodology should be used to assess the effect of specific technologies on overall project cost. The key inputs are as follows:

1. Identify the COA(s) to which a specific technology applies.
2. Identify the magnitude and kind of effect (e.g., does the technology affect off-site labor, on-site labor, or on-site materials).
3. Apply percentage changes to the components of each applicable COA.

This method is applied to various cost drivers and technology groups in Section 7 of this report.

The model developed for this analysis was built with a deterministic bottom-up approach. A bottom-up approach requires detailed drawings, piping and instrumentation diagrams (P&IDs), system design descriptions (SDDs), detailed project plans, and unit work hour data. Typically, such an approach is only suitable for mature designs, where there is enough detail to accurately detail costs for thousands of different line items. Completion of a bottom-up cost model may take over ten man-years of effort.

The revisions of the EEDB were published over the course of 11 years, with additional work beginning in the decade prior to the first publication. The granularity of the EEDB (showing off-site labor, on-site labor, or on-site materials separately for each COA) allows the user to consider the costs of each component separately. This also allows the user to identify which systems, components, and methods drive the cost of the plant.

6.2 Alternate Modeling Approaches

An alternative to the bottom-up approach is the top-down approach, which utilizes historical data to generate rules for costing structures and components, based on their size. For a nuclear power plant, some example rules would be \$/HP for pumps, \$/ft^3 (or \$/m^3) for vessels, \$/ton for steel, and \$/yd^3 (or \$/m^3) for concrete. Top-down approaches are common in the chemical process industry where unit price scales by size, as shown in the following equation:

$$Cost(\$) = A + (B * P^n) \quad \textbf{Equation 6-1}$$

Where:

- A Fixed Component
- B Base Price for Reference
- P^n Scaling Factor

This kind of approach was not considered, because it assumes that construction practices are scalable between designs, and it does not account for advances in manufacturing and construction practices that impact the cost of some components, differently than other components.

The Association for the Advancement of Cost Engineering (AACE) International provides a classification system used to grade the level of project definition as a function of how it will be used, the methodology for creating it, expected accuracy, and the level of required preparation (AACE International 2005). This system is summarized in Figure 6-1. Based on these criteria, this analysis should be considered either a Class 4 or 5.

	Primary Characteristic	*Secondary Characteristic*			
ESTIMATE CLASS	**LEVEL OF PROJECT DEFINITION** Expressed as % of complete definition	**END USAGE** Typical purpose of estimate	**METHODOLOGY** Typical estimating method	**EXPECTED ACCURACY RANGE** Typical variation in low and high ranges [a]	**PREPARATION EFFORT** Typical degree of effort relative to least cost index of 1 [b]
Class 5	0% to 2%	Concept Screening	Capacity Factored, Parametric Models, Judgment, or Analogy	L: -20% to -50% H: +30% to +100%	1
Class 4	1% to 15%	Study or Feasibility	Equipment Factored or Parametric Models	L: -15% to -30% H: +20% to +50%	2 to 4
Class 3	10% to 40%	Budget, Authorization, or Control	Semi-Detailed Unit Costs with Assembly Level Line Items	L: -10% to -20% H: +10% to +30%	3 to 10
Class 2	30% to 70%	Control or Bid/ Tender	Detailed Unit Cost with Forced Detailed Take-Off	L: -5% to -15% H: +5% to +20%	4 to 20
Class 1	50% to 100%	Check Estimate or Bid/Tender	Detailed Unit Cost with Detailed Take-Off	L: -3% to -10% H: +3% to +15%	5 to 100

Notes: [a] The state of process technology and availability of applicable reference cost data affect the range markedly. The +/- value represents typical percentage variation of actual costs from the cost estimate after application of contingency (typically at a 50% level of confidence) for given scope.

[b] If the range index value of "1" represents 0.005% of project costs, then an index value of 100 represents 0.5%. Estimate preparation effort is highly dependent upon the size of the project and the quality of estimating data and tools.

Figure 6-1
AACE International Classification System Copyright © 2011 by AACE International; All Rights Reserved (AACE International 2005)

6.3 Code of Accounts

The code of accounts (COA) system breaks out the cost components and structures into different codes. Each COA is two or three digits depending on the level of detail. The single digit COAs used in EEDB Revision IX (DOE 1987) are shown in Table 6-1. Each of these categories has subcategories, the two- and three-digit codes which are described by Table 6-2 and Table 6-3. A third level of detail for COA 21 Structures and Improvements is shown in Table 6-4.

The EEDB breaks out the constituent costs of each COA into Factory Equipment Costs, Site Labor Hours, Site Labor Cost, Site Material Cost, and Total Costs. There are some small differences among the COA used in the EEDB and the G4ECONS (EMWG, 2007).

- Contingency costs are listed as COAs X9 in EEDB but G4ECONS does not have a specific code for these costs.
- The EEDB lists general site construction, installation labor, and field supervision under the 90 series COA but G4ECONS lists these as 34-39.
- Accounts 25 (heat rejection system) and 26 (miscellaneous equipment) in the EEDB are switched in G4ECONS.
- The latest edition of G4ECONS does not include the cost of the first core. Previous versions of G4ECONS did.

The COA structure used in this report is consistent with that recorded in EEDB Revision IX for the PWR12 ME (DOE 1988). The EEDB ME is for an 1144 MWe PWR with a primary side operating pressure of 2250 psia (155 bar) and an NSSS thermal power rating of 3431 MWt. The EEDB Median Estimate (ME) was used rather than the “Best Case” because the best case includes some assumptions about advancements in construction technology. The ME did not assume any advancements and is therefore a better base case for evaluating the effects of the advanced technologies proposed in Section 7.

In order to update the model, so it could be better used to assess the effect of improvements on schedule and adjust the results to 2017 dollars, some minor changes were made to the constituent items for each three digit COA (i.e., factory equipment cost, site labor cost, and site materials cost). However, the magnitude of each code is consistent with the EEDB Revision IX.

Table 6-1
Two Digit Code of Accounts

Code	Category	Cost Input Mechanism
10s	Preconstruction Costs	Line-Item Adjustment Multipliers
20s	Direct Construction Costs	Line-Item Adjustment Multipliers
30s	Indirect Services Costs	Design Standardization Reduction Factor and Line-Item Adjustment Multipliers
40s	Owner's Costs	Line-Item Adjustment Multipliers
50s	Supplementary Costs	Line-Item Adjustment Multipliers
60s	Financing During Construction	Construction Duration for Calculating Interest
70s	O&M Costs	Line-Item Adjustment Multipliers
80s	Fuel Costs	User-Defined Values (or Defaults)
90s	Financing During Operation	Line-Item Adjustment Multipliers

Table 6-2
Description of Three-Digit COA for Direct Costs

Two-Digit COA	Scope	Purpose	Examples	Three-Digit COA	Scope COA
20	Preconstruction Activities	Secure rights and permission to construct the plant	• Land and land/water rights • Site permits • Plant licensing • Plant permits • Plant studies • Plant reports	210	Preconstruction Activities
21	Structures and Improvements	House and support equipment, components, piping, ducting, wiring, fire protection, mechanical, electrical and plumbing personnel, access, habitability structures	• On-Site Surface Buildings • Subsurface Foundations • Tunnels • Site Improvements *Clearing* *Excavation* *Grading* *Roadways* *Rail Spurs* • Buildout/detailing • Does not include *Equipment Pedestals* *Heat Reject Building*	211	Yardwork
				212	Reactor Containment
				213	Turbine Building and Heater Bay
				214	Security Buildings
				215	Prim Aux Building and Tunnels
				216	Waste Processing Building
				217	Fuel Storage Building
				218A	Control Room/DG Building
				218B	Admin and Service Building
				218D	Fire Pump House
				218E	Emergency Feed Pump Building
				218F	Manway Tunnels (RCA)
				218G	Electrical Tunnels
				218H	Non-Essential Switchgear
				218J	Main Steam and FW Chases
				218K	Pipe Tunnels
				218L	Tech Support Center
				218P	Equipment Hatch Missile Shield
				218S	Wastewater Treatment
				218T	UHS Structure
				218V	MCR Air Intake Structure

Table 6-2
Description of Three-Digit COA for Direct Costs (continued)

Two-Digit COA	Scope	Purpose	Examples	Three-Digit COA	Scope COA
22	Reactor Plant Equipment	Support, contain, and control the nuclear fuel heat source and provide means of transferring energy to electrical generation system	• Reactor • Reactivity control • Safety systems • Radwaste handling • Interconnected piping • Reactor I&C • Reactor environment systems	220A	Nuclear Steam Supply (NSSS)
				220B	NSSS Options
				221	Reactor Equipment
				222	Main Heat Transfer Export System
				223	Safe Guards System
				224	Radwaste Processing
				225	Fuel Handling + Storage
				226	Other Reactor Plant Equipment
				227	Reactivity Control I&C
				228	Reactor Plant Miscellaneous
23	Turbine Plant Equipment	Convert energy from reactor plant to electricity using steam	• Turbine • Generator • Pedestal • Steam Piping • Auxiliary systems • Exciter • Stator cooling • Hydrogen • I&C • Safety systems	231	Turbine Generator
				233	Condensing Systems
				234	Feed Heating Systems
				235	Other Turbine Plant Equip
				236	Turbine I&C
				237	Turbine Plant Miscellaneous

Table 6-2
Description of Three-Digit COA for Direct Costs (continued)

Two-Digit COA	Scope	Purpose	Examples	Three-Digit COA	Scope COA
24	Electric Plant Equipment	Deliver electricity from turbine plant to grid plus provide auxiliary electric power (house loads), standby and emergency power	• Cables • Raceways • Switchgear • Structural supports • Generator controls • Lighting protection • Cathodic protection • Does not include House lights/power	241	Switchgear
				242	Station Service Equipment
				243	Switchboards
				244	Protective Equipment
				245	Electrical Structure and Raceways
				246	Power and Control Wiring
26	Main condenser heat rejection system including intake	Dispose of heat rejected by plant and provide treated makeup water	• Cooling tower • Interconnected piping • Makeup water system • Pumps	261	Structures
				262	Mechanical Equipment
25	Miscellaneous Plant Equipment	Support plant startup, operation, and maintenance.	• Cranes • Air, water and steam • Auxiliary boiler • Fire protection • Communications • Non-rad water treatment • Plant monitoring • Furnishings and fixtures • Supports	251	Transport and Lifting Equipment
				252	Air, Water, and Steam Sys
				253	Communications Systems
				254	Furnishing and Fixtures
				255	Waste Water Treatment

Table 6-3
Description of Three Digit COA for Indirect Costs

Two-Digit COA	Scope	Purpose	Examples	Three-Digit COA	Scope COA
91	Construction Services	Support construction and preservation of plant during construction and commissioning	• Building • Shops • Janitorial • Security • Roads • Laydown • Temp services	911	Temporary Construction Facilities
		Facilitate plant construction through purchase or rental of equipment, tools and consumables (e.g., fuel)	• Equipment • Tools • Cranes • Vehicles • Mix plants	912	Construction tools and equipment
		Support project by paying required taxes	• Social security • Unemployment • Workman's comp • Liability insurance	913	Payroll insurance and taxes
		Support project by paying requisite insurance	• Contractor's insurance • Local fees • Nuclear liability insurance	914	Permits, Insurance and Local Taxes
		Provide vehicles for onsite construction support	• Automobiles • Trucks • Other	915	Transportation

Table 6-3
Description of Three Digit COA for Indirect Costs (continued)

Two-Digit COA	Scope	Purpose	Examples	Three-Digit COA	Scope COA
92	Engineering and Home Office Services	Perform tasks required for project execution both on and offsite	• Field Engineering • Procurement • Planning and scheduling • Cost control	921	Home Office Services
		Support design, build, and test per regulations	• QA • QC • Program support (audits)	922	Home Office Quality Assurance
		Provide services required to execute the build	• Construction mangers • Planning and scheduling (construction) • Develop construction methods • Labor relations • Safety and security	923	Home Office Construction Management
93	Field Supervision and Field Office Services	Provide infrastructure for build	• Furniture and fixtures • Communications	931	Field Office Expense
		Provide services required to execute the build	• Superintendents • Admin support • Schedulers • Work control • Purchasing • Warehouse	932	Field Job Supervision
		Support project execution with QA/QC services	• QA • QC • Programmatic	933	Field QA/QC
		Support plant commissioning	• Personnel	934	Plant Startup and Test

Table 6-4
EEDB and EMWG Structures and Improvements COA

COA	Description	Factory Equipment Costs ($)	Site Labor Hours (MH)	Site Labor Cost ($)	Site Material Cost ($)	Total Costs ($)
21	Total	22,529,314	5,320,188	113,513,274	64,701,510	200,744,098
211	Yardwork	284,275	752,423	14,504,359	10,203,885	24,992,519
212	Reactor Containment	14,269,940	1,629,225	35,626,866	14,939,235	64,836,041
213	Turbine Building and Heater Bay	621,415	504,203	11,172,557	11,358,358	23,152,330
214	Security Buildings	51,921	43,999	942,705	367,329	1,361,955
215	Prim Aux Building and Tunnels	3,142,227	488,600	10,519,814	4,810,104	18,472,145
216	Waste Processing Building	651,097	425,075	9,023,634	4,692,587	14,367,318
217	Fuel Storage Building	997,541	209,485	4,505,021	4,376,541	9,879,103
218A	Control Room/DG Building	1,463,812	514,375	11,180,489	5,454,347	18,098,648
218B	Admin and Service Building	820,374	152,210	3,391,564	2,434,409	6,646,347
218D	Fire Pump House	39,449	11,000	239,463	147,914	426,826
218E	Emergency Feed Pump Building	22,323	81,354	1,710,063	766,078	2,498,464
218F	Manway Tunnels (RCA)	-	25,572	539,020	222,881	761,901
218G	Electrical Tunnels	9,633	1,728	42,174	15,963	67,770
218H	Non-Essential Switchgear	19,150	13,143	289,217	227,530	535,897
218J	Main Steam and FE Chases	33,210	246,245	5,285,231	2,548,723	7,867,164
218K	Pipe Tunnels	-	9,792	204,526	112,775	317,301
218L	Tech Support Center	51,921	24,168	497,324	240,200	789,445
218P	Equipment Hatch Missile Shield	-	8,243	167,580	52,348	219,928
218S	Wastewater Treatment	8,307	23,524	483,775	275,210	767,292
218T	UHS Structure	42,719	152,781	3,127,087	1,426,765	4,596,571
218V	MCR Air Intake Structure	-	3,043	60,805	28,328	89,133

6.4 Assumptions and Inputs

The assumptions used in the model are described in the subsections below.

6.4.1 Base Year

The base year used in the analysis was 2017, in order to maintain consistency with MIT's *The Future of Nuclear Energy in a Carbon-Constrained World* (MIT 2018) and with the work completed by Argonne National Laboratory (Ganda 2019 Appendix A).

6.4.2 Debt to Equity and WACC

The role of debt to equity in large construction projects has a substantial effect on overall project cost because investors with equity in the project are willing to accept a lower rate of return. The weighted average cost of capital (WACC) is a useful metric to estimate the actual rate of return when projects are funded partially by debt and partially by equity.

$$WACC = [d(1 - tr)dR] + [e(1 - dR)] \quad \textbf{Equation 6-2}$$

Where:

d real rate of return on debt

tr corporate tax rate

dR the debt to total capitalization ratio, [*d*/(*d*+*e*)]

e real rate of return on equity

Rothwell provides an example WACC for nuclear power assuming straight-line depreciation with 50% debt, 50% equity, a 38% tax rate, a real cost of debt of 7.5%, and a nominal cost of equity of 18% yields a nominal WACC of 12% and a real cost of capital of 10% (Rothwell 2015). IEA and NEA use WACC of 3%, 7%, or 10% (IEA and NEA, 2015). In this analysis, a discount rate of 7% was assumed, consistent with IEA's median case.

6.4.3 Inflation Adjustment (GDP Deflator, CPI, Means)

There are some common ways to convert prices between years. The Consumer Price Indicator (CPI) Index (Coinnews 2019), RSMeans CCI (RSmeans 2018), and ENR Construction Index (BNP Media 2017) are shown in Table 6-5. Each of these methods can be used to convert the cost from an original year to the present year according to Equation 6-3. In this analysis, the ENR Construction indices were used. The other indices are included for ease of comparing the results of these analyses to other analyses which rely on those methods. Although not recorded in Table 6-5, it is observed that some prominent cost studies use the CERA Power Capital Cost Indices, which has a similar basis (Rothwell 2015).

$$Cost(\$_{Present}) = \frac{Index_{Present}}{Index_{Original}} Cost(\$_{Original}) \quad \textbf{Equation 6-3}$$

Table 6-5
Cost Indices Used to Compare the Cost of Construction

Year	CPI	RSMeans CCI	ENR Construction	Year	CPI	RSMeans CCI	ENR Construction
1980	82.4	62.9	3237.0	2003	184.0	132.0	6694.0
1981	90.9	70.0	3535.0	2004	188.9	143.7	7115.0
1982	96.5	76.1	3825.0	2005	195.3	151.6	7446.0
1983	99.6	80.2	4066.0	2006	201.6	162.0	7751.0
1984	103.9	82.0	4146.0	2007	207.342	169.4	7966.0
1985	107.6	82.6	4195.0	2008	215.303	180.4	8310.0
1986	109.6	84.2	4295.0	2009	214.537	180.1	8570.0
1987	113.6	87.7	4406.0	2010	218.056	183.5	8799.0
1988	118.3	89.9	4519.0	2011	224.939	191.2	9070.0
1989	124.0	92.1	4615.0	2012	229.594	194.6	9308.0
1990	130.7	94.3	4732.0	2013	232.957	201.2	9547.0
1991	136.2	96.8	4835.0	2014	236.736	204.9	9806.0
1992	140.3	99.4	4985.0	2015	237.017	206.2	10035.0
1993	144.5	101.7	5210.0	2016	240.007	207.3	10338.0
1994	148.2	104.4	5408.0	2017	245.120	213.6	10403.917
1995	152.4	107.6	5471.0	2018	251.107	222.9	-
1996	156.9	110.2	5620.0	-	-	-	-
1997	160.5	112.8	5826.0	-	-	-	-
1998	163.0	115.1	5920.0	-	-	-	-
1999	166.6	117.6	6059.0	-	-	-	-
2000	172.2	120.9	6221.0	-	-	-	-
2001	177.1	125.1	6343.0	-	-	-	-
2002	179.9	128.7	6538.0	-	-	-	-

6.4.4 Learning Curve (LC) and FOAK/NOAK

It is generally acknowledged, that one major barrier to new nuclear construction is the uncertainty over cost and schedule, typical of FOAK projects. Other countries have addressed these concerns by completing 100% design prior to starting construction. The impact of project planning is demonstrated with Figure 6-2 (data includes foreign projects). FOAK plants have two primary cost categories: costs of construction (that are shared with NOAK units) and costs that are related to design and certification of the first unit (EMWG 2007). This analysis is not focusing on mitigating risks specific to FOAK construction, but on identifying technologies that affect the cost drivers of NOAK construction (and thus the FOAK).

In order to realize the benefits of a learning curve, only incremental improvements can be made to the design for subsequent reactors. This is best illustrated by Figure 6-3 which shows the difference between the actual cost of Sizewell B and the proposed cost of Sizewell C, compiled directly after completion of Sizewell B by the Unit B design team. Although Sizewell C was not built, this figure shows the type of savings that can be achieved. Some experts are skeptical that NOAK benefits can even be achieved in the U.S. nuclear industry (Rothwell 2015). There is further skepticism over how many units must be built before the learning curve flattens out and significant incremental improvements are achieved. Estimates range from 8 to 32 GW (EMWG 2007, DOE 1987, Rothwell 2015).

For simplicity, this study focuses on technologies that can benefit all nuclear construction (i.e., benefits realized by the FOAK and NOAK unit). The savings of these technologies are shown in reference to NOAK estimates. It is possible that larger benefits could be achieved by using these technologies on an FOAK unit because the proposed technologies decrease the price of an NOAK unit as well as decrease the risks of FOAK construction.

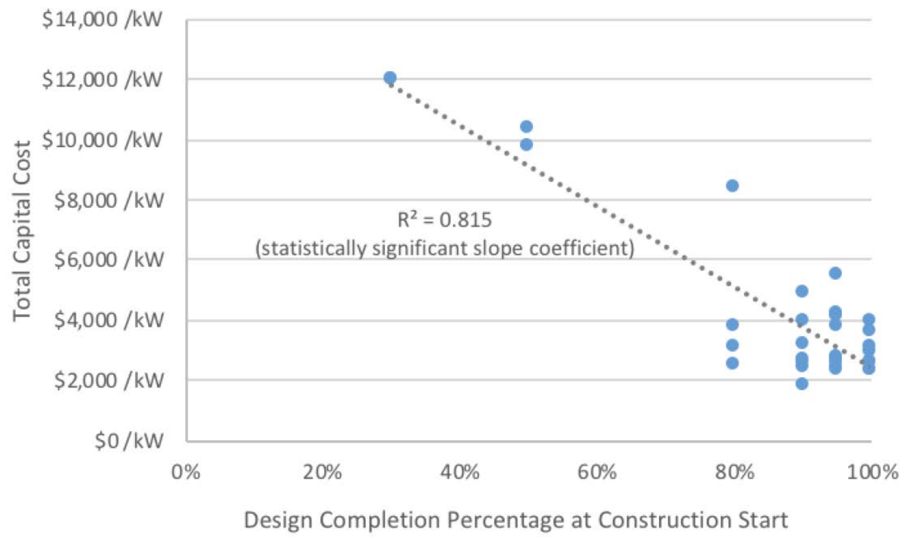

Figure 6-2
Total Capital Cost as a Function of Design Completion (Ingersoll 2019 Appendix A)

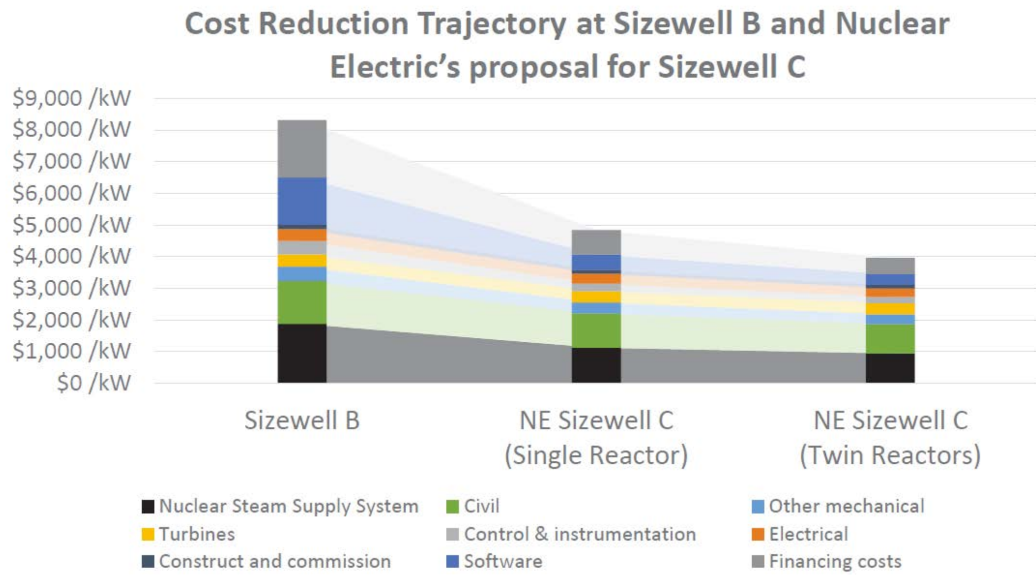

Figure 6-3
Cost Reduction Trajectory of Proposals for Sizewell C (Ingersoll 2019 Appendix A)

6.4.5 Fuel Cost

It is noted that some cost estimates include the cost of the first core as part of OCC, while some don't. In these analyses, the first core load was included as part of OCC. Subsequent fuel costs were included as part of variable O&M, which were assumed to be $10/MWh, the value stated in the U.S. Energy Information Administration's latest report on reference costs (U.S. EIA 2019). This assumption is consistent with other references (e.g., Champlin 2018).

6.4.6 Standard Work Hour Data

When construction firms estimate labor costs for large projects they use "standard work hour data" which are experience-based correlations between material quantities and labor hours needed to build the structures. No particular standard work hour data sets were used as part of this analysis. Instead, labor rates were based on the labor hours and costs stated in EEDB.

6.4.7 Productivity Factors

There are well established differences in worker productivity country to country, especially in the construction industry (MIT 2018). In this analysis it was assumed that the labor costs were similar to those presented in the EEDB extrapolated from 1987 to 2017 (Section 6.4.1 to 6.4.3). Although a specific productivity factor was not assumed, the DOE study was based on U.S. experience, so it is assumed that the productivity of the labor force would be typical of a U.S. force.

6.4.8 Inclusion of Balance of Plant in Cost Estimates

There are three main contract types that have been utilized for the construction of nuclear power plants and govern ownership of parts of the design. In a turnkey approach (top of Figure 6-4), the owners hire one firm to manage the designs of both the nuclear island and the conventional island (or balance of plant). This approach minimizes the number of stakeholders needed to make design decisions and allows for a nimbler resolution of design issues. A split approach (middle of Figure 6-4) has two primary engineering and design firms: one responsible for the nuclear island and the second for the balance of plant. The final contract type (bottom of Figure 6-4) further divides the islands and add additional design firms responsible for different systems within each island. As the number of design firms increases, so does the number of interfaces between them.

It is recognized that separation of the plant, either by safety classification or by contract has potential cost saving advantages. However, it was beyond the scope of this study to quantify such benefits due to the lack of available data for estimating savings from changes in the design approach.

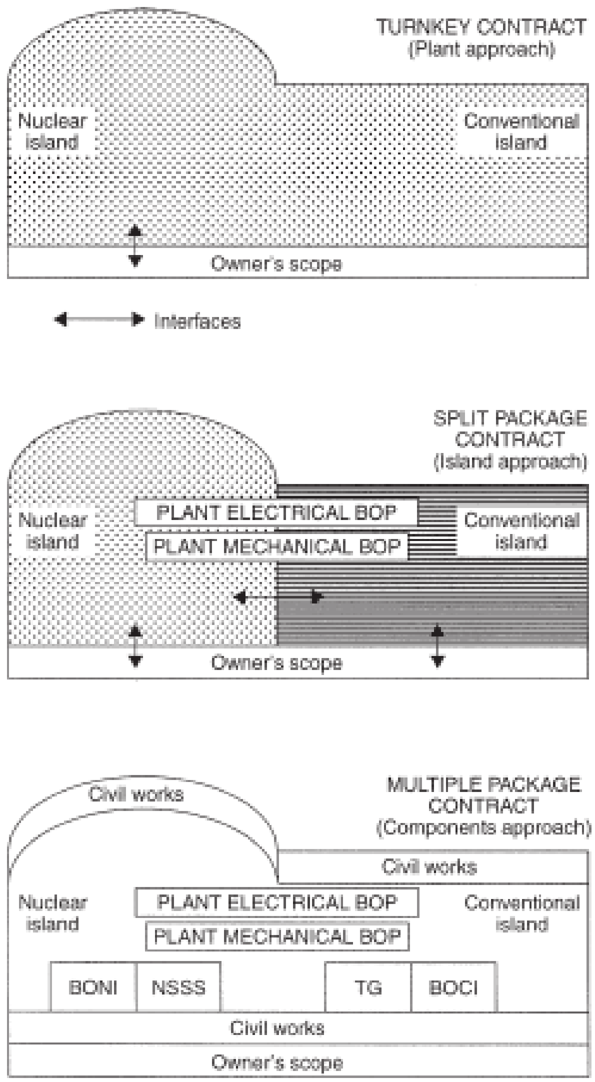

Figure 6-4
Three Types of Contracts: Turnkey, Split Package, or Multiple Package. Figure Used with Permission from IAEA. All Rights Reserved by IAEA. (IAEA 2000)

6.4.9 Construction Labor Rates

Labor rate differences between different countries can have significant effects on the final OCC. Some sample construction labor rates for common cost categories in NPP construction projects are shown in Table 6-6. The analyses performed for this project use the labor rates from the EEDB Phase IX (DOE 1988, which assumes the project will be built in Middletown, U.S.) adjusted for inflation using the ENR scaling factors (see Section 6.4.3). The values documented in Table 6-6 were not used, but they are shown to demonstrate the variability in labor rates between countries.

Table 6-6
Standard Labor Rates for U.S., Korea, EU, and China (Varrin 2018)

Category	Job Title	USA	Korea	EU	China
Management	Plant/Project Manager	$ 135	$ 85	$ 95	$ 53
Engineering	Professional engineer (highest)	$ 87	$ 52	$ 57	$ 36
	Advanced engineer	$ 72	$ 34	$ 44	$ 15
	Intermediate engineer	$ 45	$ 28	$ 33	$ 13
	Elementary engineer	$ 33	$ 24	$ 19	$ 7
	Highly Skilled technician	$ 33	$ 29	$ 21	$ 3
	Intermediate skilled technician	$ 25	$ 26	$ 15	$ 3
	Elementary skilled technician	$ 20	$ 16	$ 12	$ 2
Construction Supervision	Manager	$ 88	$ 55	$ 58	$ 20
	Site Engineer (average)	$ 62	$ 28	$ 32	$ 14
	Construction Supervisor	$ 55	$ 34	$ 53	$ 20
	Shift Supervisor of Craft Labor	$ 39	$ 34	$ 32	$ 18
Craft	Carpenter	$ 35	$ 23	$ 22	$ 1
	Pipefitter	$ 44	$ 23	$ 20	$ 1
	Electrician (master)	$ 48	$ 26	$ 29	$ 2
	Electrician (normal)	$ 35	$ 20	$ 22	$ 1
	Welder (nuclear)	$ 51	$ 16	$ 31	$ 5
	Weld Inspector	$ 40	$ 28	$ 22	$ 1
	Steelworker (rebar)	$ 29	$ 18	$ 18	$ 1
	Rigging Supervisor	$ 52	$ 28	$ 20	$ 5
	Rigger	$ 30	$ 18	$ 13	$ 1
	Laborer (high)	$ 26	$ 18	$ 13	$ 1
	Laborer (low)	$ 12	$ 7	$ 11	$ 1
Quality	QA Manager	$ 63	$ 62	$ 58	$ 15
	QA Engineer	$ 43	$ 28	$ 32	$ 7
	QA/QC Technician	$ 25	$ 26	$ 24	$ 3
Safety	Manager	$ 52	$ 50	$ 32	$ 15
	Safety Person	$ 32	$ 18	$ 24	$ 2

6.4.10 Operating & Maintenance Costs (O&M)

Multiple references assumed O&M costs to be roughly 15-25% of the total LCOE (Rothwell 2015, Ganda et al. 2018, U.S. EIA 2016, Champlin 2018). Other reference reports these costs as function of plant size or other criteria, but these estimates are generally of a similar magnitude. In this analysis, it was assumed that O&M costs were $13/MWh, the value stated in the U.S. Energy Information Administration's latest report on reference costs (U.S. EIA 2019).

6.4.11 Causes for Increase in PWR12ME Costs Exceeding Inflation

EEDB cost estimates for Phase I through Phase IX increased at a rate higher than the reported inflation. These increases were largely due to design changes required by increasingly stringent regulations and incorporation of new construction practices. These design expansions lead to increases in both direct and indirect costs. Some of the identified areas in which these costs are most significant are as follows:

- Design changes in areas related to structural components (e.g. increased quantities of embedded steel), piping, raceways, and wire/cable quantities
- Productivity decreases caused by design changes, interferences, incomplete documentation, or back fitting that caused rework
- Increased stringency in regulatory requirements or interpretation of requirements, particularly with respect to tolerances and worker qualification/requalification
- Special training for safety-class installation procedures and documentation
- Productivity decreases related to material and tool unavailability, crew interferences, overcrowded work areas, and inspection delays
- Increased real labor costs due to schedule slippages, leading to increased use of multiple shifts and cash flow problems
- Standard changes that increased the complexity of design requirements
- Increased indirect costs related to the increases in direct costs (i.e., additional construction management related to added scope)

The rate of increase in indirect costs was significantly greater than the rate of increase in direct costs. This can be partially attributed to increased construction duration (discussed further in Section 6.4.12).

6.4.12 Effect of Construction Time on Indirect Costs

Indirect costs comprise three categories: 1) fixed costs to erect temporary facilities used in construction; 2) costs that scale with the size of the project such as tools, laydown areas, and warehouses used for storage; and 3) time-related costs including rentals, site cleanup, and maintenance of temporary facilities (EMWG 2007).

Two methods were used to estimate the effect of schedule on indirect costs. The first method (EMWG method) is a top-down method based on statistical regression of plant experience (schedule versus indirect) and is therefore "experienced based". EMWG provides two equations which can be used to determine the length of construction on the indirect costs for the nuclear island (Equation 6-4) and the balance of plant (Equation 6-5). In both equations, the first term is used to calculate the fixed costs, the second the costs that scale, and the third the time related costs.

$$Indirect_{NI} = 6.85x10^6\left(\frac{P}{1200}\right)^{0.33} + 0.48LN + 4.30x10^6\left(\frac{P}{1200}\right)^{0.5}M$$ **Equation 6-4**

$$Indirect_{BOP} = 6.85x10^6\left(\frac{P}{1200}\right)^{0.66} + 0.34LN + 4.30x10^6\left(\frac{P}{1200}\right)M$$ **Equation 6-5**

Where:

P Plant rating (MWe)

LN Labor cost

M Construction duration (Months)

Figure 6-5 shows the indirect labor costs for an 1144 MWe for construction lengths ranging from two to ten years given an average loaded labor rate of $110.17/hr and that the schedule affects an estimated 1000 workers on site. Also noted on the figure are the world record construction time achieved during the construction of 54 months and the 72 months (the length assumed in these analyses). The average loaded labor rate was calculated so this equation matches the total indirect cost predicted by the model shown in Section 7.

Equation 6-4 and Equation 6-5 predict that reducing the construction time from 72 months to 55 months results in savings of $199/kW for the NI, $257/kW for the BOP, and $456/kW total.

The second method was the model developed for this project. The model scales indirect costs based on the factors that drive them: number of workers on site, cost rate for individual indirect activities, duration of activities. This additional granularity allows for modeling, in order to account for the following factors.

- A schedule reduction later in the build period, will reduce the LCOE more than a schedule reduction of the same length earlier in the period, because less money has been spent and less interest will be owed on a larger fraction of OCC.
- Indirect costs are greater during specific periods of the build, due to the activities taking place during those periods. Schedule reductions during the periods where indirect costs are higher, may results in significant savings than schedule reductions during other periods.

Both of these methods are used in Section 7 of this report. The EMWG method was used when assessing the magnitude of the civil and structural design and craft labor cost drivers because a more general experienced based relationship between indirect costs and duration was required. The cost estimating tool was used when estimating the savings from example project types (Section 7.3) because the assumed technologies reduced construction costs during specific windows.

One of the main conclusions of this report is that the most significant cost reduction strategies are those that are able to reduce construction duration in addition to savings in labor and to a lesser extent materials. These savings are amplified even more when accounting for reduced interest costs during construction.

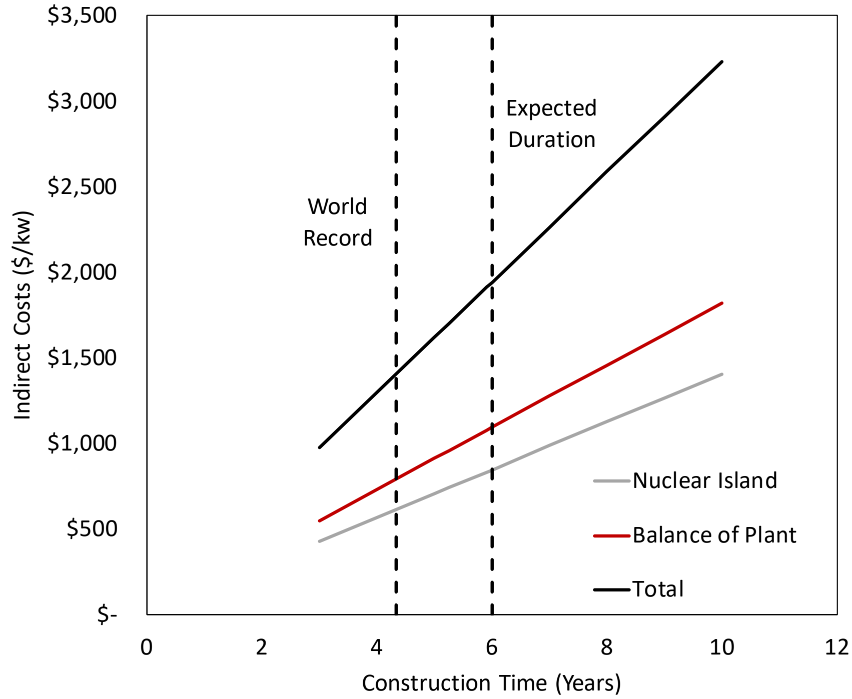

Figure 6-5
Indirect Costs as a Function of Construction Time

6.5 Out of Scope Technologies

The following technologies were determined to be beyond the scope of the research documented in this report.

6.5.1 ATF Credits

This study assumed that there were no credits for accident tolerant fuel (ATF). It is expected that at some point in the future, this technology will provide savings to plants that utilize them.

The main savings from ATF use could result from reducing the size of the existing emergency planning zone (EPZ). A survey of the existing fleet showed that maintain the existing EPZs costs an average of $2.25 million per year, with an additional $10 million in startup costs (INL 2014). ATF could be used as a technical justification for reducing the EPZ from ten miles to the site boundary, resulting in a reduction of the offsite emergency planning costs by 90% over the plant’s lifetime. Smaller cost savings are also possible if the EPZ is reduced to a 2- or 5-mile zone (from the existing ten miles).

Additional savings may be achieved from increases in fuel burnup and cycle length. These savings could also result in significant cost savings from fuel purchases and fuel disposal (dry casking). Smith (2019) suggests amortized savings of approximately $3.5B in the U.S. or about $35M per unit.

Finally, significant savings can also be achieved from the use of ATF if safety assessments can support the downgrading of some systems, from a safety-related to a non-safety-related category. However, many new nuclear plant designs take an alternate approach to safety systems by using passive safety or inherently safe technologies. Therefore, savings of this type are not expected to be significantly relevant to most nuclear-power new builds.

6.5.2 Seismic Isolation

Seismic isolation can be used to make structures less effected by earthquakes. There are three primary types of isolators that are used by structural designers and the construction industry to reduce the effects of seismic-related ground motions. These are low damping (natural) rubber (LDR) isolators, lead (natural) rubber (LDR) isolators, and the Friction Pendulum (FP) sliding isolator (Whittaker et al. 2014). The benefit of seismic isolation systems can extend to both the loading demands for the site structures and components. To date, six units at two different sites (two units at Koeberg in South Africa and four units at Cruas in France), have been built using seismic isolation.

EPRI has other ongoing research projects focused on this area and the potential savings from seismic isolation are not further discussed in this analysis.

7
ASSESSMENT OF ADVANCED TECHNOLOGIES (MODEL RUNS)

The main focus of this research is two-fold: (1) to develop a framework for understanding what factors drive the cost of NOAK nuclear power plants and (2) to provide a tool that can be used to assess the effect potential technologies will have on the cost of new plants.

Section 7.1 describes the cost drivers identified during the EPRI/GAIN/NEI development workshop meeting from January 2019 (see Appendix A). Note that several prior workshops and meetings were used as input to the initial discussions and are therefore incorporated into the Appendix A materials.

Section 7.2 introduces the spreadsheet model created for this analysis and presents a quantitative analysis for five of the selected cost drivers: (1) craft labor costs, (2) civil/structural design, (3) constructability of design, (4) materials, and (5) inspection (QA/QC). The analysis leverages other work estimating how much each cost driver could be reduced.

Section 7.3 groups potential solutions into six technology groups. These technologies are grouped based on the primary way in which they reduce the cost of new plants (e.g., on-site materials, on-site labor). It is also acknowledged that many technologies that address the cost drivers will affect multiple COAs in multiple ways (e.g., reductions in material and labor costs). The primary function of the technology groups is to provide examples of how this model can be used to evaluate particular solutions, and to demonstrate the magnitude of solutions that fall into these categories.

7.1 Cost Drivers

Representatives from EPRI, NEI, DOE, and electric utilities, as well as other industry experts, gathered at the EPRI/GAIN/NEI co-sponsored workshop held in Washington, D.C. on January 17-18 (EPRI 2019 Appendix A), and identified the cost drivers discussed in the following cost driver analysis. Also, input from previous meetings of similar groups (February 2018 in Washington, D.C.; March 2018 in Charlotte, NC; June 2018 in Charlotte, NC; and November 2018 in Charlotte, NC) were summarized and used as the starting point for this meeting.

Most of the improvement factors cited in this section are consistent with those cited in the EEDB Phase IX (DOE 1988), which provides a comparison of each COA, between the Improved PWR12 (IPWR12) and the PWR12BE. Although the base COA used to create this model's baseline were those of the PWR12ME, the comparison between the IPWR12 and the PWR12BE provide reasonable improvement factors for decreasing the costs of these COA. The improved model makes a few assumptions that reduce its direct costs, compared to the PWR12BE. These include:

- Some use of digital I&C (plant protection system remains a hard-wired system)
- Standardized design that did not require significant site-specific adaptations
- Modular off-site construction was limited largely to non-structural elements of the turbine (e.g., the turbine pedestal was excluded) and auxiliary building facilities. However, the study mentioned but did not describe in detail use of modularity for equipment piping and wiring modules including some portions of equipment inside containment. It was also assumed that the Modular Assembly Site (MAS) was within 100 miles of the plant and the modules were sized to be transportable by barge.
- A plant design that was lower in overall height, in order to reduce the amount of structural steel and facilitate installation of modules, partially by changing the sequence of construction (fewer vertically stacked components renders sections of equipment more independent) – this was referred to as a backbone approach to modular construction.

These assumptions decreased site labor and materials costs, but typically increased factory equipment costs. Larger savings were found in indirect costs, because it is assumed that more of the engineering was complete prior to the start of construction and that construction would take 63 months instead of 72 months, which is the period assumed for the PWR12BE. In total, the base costs of the IPWR12 model were 17% lower than those of the PWR12BE.

The DOE noted in the study that the level of improvement afforded by the IPWR12 design was conservative and that they expected that actual realization of a plant that was designed to take advantage of and then incorporate new features, such as modular construction and digital I&C, would actually be greater.

7.1.1 Craft Labor Costs

McKinsey Global Institute published a 2017 report with a focus on improving productivity of construction related services worldwide (McKinsey 2017). The report identifies seven areas that in conjunction could boost labor productivity by 50-60%:

- Reshape regulation and raise transparency – Some countries have enabled productivity gains by eliminating regulatory burdens.
- Rewire contractual framework – Hostile contracts are characteristic of the construction industry and pit buyers against their workforce. Contracts should be incentive-based, in order to reward the workers for progress. Alternative contracting models, such as integrated project delivery (IPD), should be explored.
- Rethink design and engineering processes – Projects should be designed for constructability and ease of assembly. This includes incorporating repeated design elements which allow the workforce to become more skilled as the project progresses.
- Improve procurement and supply chain – Improved communication between suppliers and contractors will result in decreased delays and allow resources to be deployed when they are needed.

- Improve onsite execution – Four key concepts were identified. 1) Instituting a more rigorous planning process such as Last Planner System (LPS). 2) Reshaping the relationship and interactions between owners and contractors to focus on key performance indicators (KPI). 3) Improving mobilization so all approvals and pre-work is completed prior to the scheduled start of work activities. 4) Incorporating lean operating principles that rely on a holistic approach instead of traditional command and control processes.
- Infuse technology and innovation – Utilization of BIM and other advanced planning software.
- Reskill workers – Training workers to use the technologies and method discussed in the other bullets.

Together, these concepts could increase worker productivity by 50-60%, and decrease craft labor costs by the same amount.

The following solutions were identified at the EPRI/GAIN/NEI meeting held in Washington D.C, as ways of increasing worker productivity (EPRI 2019 Appendix A):

- Increase appropriate use of artificial intelligence (AI) and machine learning
- Increase appropriate use of augmented reality
- Incentivize personalized productivity
- Improve training/qualification
- Develop ways to automate construction
- Link the use of a smart batch plant with in-situ work activities
- Reduce paperwork slowness

Through some combination of the above technologies and concepts, it is assumed that increases in worker productivity can decrease total labor hours spent by 50%. It is also assumed that this change will shorten the expected project duration from 72 months to approximately 55 months, as achieved in several different nuclear projects in Japan, South Korea, and China in the 1990s and early 2000s (IAEA 2019). The equations shown in Section 6.4.12 show that this change in product duration would further decrease indirect costs by 24% ($456/kW).

Table 7-1
Potential to Improve Productivity (Data from McKinsey 2017)

Enhancer Type	Productivity Enhancers	Cost Savings Potential
External Forces	Regulation	Enabler of the other forces
Industry Dynamics	Collaboration and Contracting	6-7%
Industry Dynamics	Design and Engineering	7-10%
Firm-Level Operational Factors	Procurement and Supply Chain Management	3-5%
Firm-Level Operational Factors	On-Site Execution	4-5%
Firm-Level Operational Factors	Technology	4-6%
Firm-Level Operational Factors	Capability Building	3-5%
	Total	**27-38%**

7.1.2 Baseline Civil/Structural Design Costs

The civil and structural components of a light water reactor are much larger than the similar structures present in fossil plants and make NPP construction sites some of the largest in the world. This, in part, is due to the complexity and scale of the equipment but is also due to the size of the structures that are housing that equipment. For modeling purposes, it was assumed that each of the COA discussed in Section 7.1.3 are also applicable.

Civil and structural design costs can be improved through proper application of modularity, increased use of factory fabrication, and some advanced building technologies such as steel-plate composites or use of ultra-high performing concrete and other metals.

The benefits of modularity are often illustrated by the “1-3-8” rule, which is a rule of thumb developed for the shipping industry. This rule provides estimated multipliers for the cost of completing activities in a factory (1x), at an on-site assembly area (3x), or in place (8x). This rule has questionable applicability to the nuclear industry, but it is often cited as an example of the benefits of modularity.

Constructing the plant in modules decentralizes the construction activities and allows more operations to be completed in parallel. Completing activities on a factory floor allows environmentally sensitive activities to be completed in controlled environments. Completing these activities faster reduces labor costs and condenses schedule. In addition to construction activities, some testing and inspections can be completed prior to components arriving on site. Completing inspections off-site allows identified flaws to be corrected without disrupting onsite activities (Maronati 2018).

Three different modular construction strategies are defined in Figure 7-1.

- Strategy 1: Complete Modularization – Modules are assembled in the factory, assembled into super modules in a laydown area, and work in place is limited to installation of the super modules.
- Strategy 2: Partial Modularity – Modules and super modules are assembled in the assembly area instead of in the factory and are then installed in place. Because the total number of modules and super modules is greater than in Strategy 1, total time needed for installation in place is greater. Furthermore, limited work on the factory floor prevents the plant from receiving the benefits of performing work in a controlled environment (e.g., lower manufacturing variability, reduced maintenance to fix manufacturing defects, performing inspections off-site).
- Strategy 3: Stick Built – Strategy 3 does not include wide-use of modularity. Minimal modules are built in the factory and no super modules are constructed. The lack of an assembly area maximizes the amount of construction activities that must be constructed in place.

Maronati (2018) completed Monte Carlo analyses to combine uncertainties in activity durations and equipment costs for the construction of the WEC-SMR Nuclear Island. Although this is not the same plant design as PWR12ME (the model nominally used throughout this analysis), the time estimates developed demonstrate the benefits of modularity for nuclear construction projects. These analyses calculated construction times of 1701 days, 1642 days, and 2315 days, for Strategies 1, 2, and 3, respectively. Strategy 1 has a longer construction time despite having more modularity, because of the time needed to ship components from the factory to the site location. The modular strategies (1 and 2) resulted in significantly lower OCC and TCIC than the stick built strategy (3). The savings on Base Cost (BC) were relatively greater than the savings in OCC and TCIC, because modular construction pushes some construction costs earlier in the construction process. In Section 7, it was assumed that OCC savings of 30% were possible with proper use of modular construction.

Westinghouse’s AP1000 was designed with a specific focus on utilizing modularity. The use of modules at Sanmen in China allowed builders to place 2500 tons of modules in less than 100 days (Walker 2011). However, other AP1000 projects have seen significant delays. The specific reasons those projects were delayed were not related to use of modules, and therefore do not detract from the optimistic assumptions about the benefits of modularity presented in this report. It was assumed that if modularity were used to an effective degree, baseline civil and structural design costs could be decreased by 30%.

It is also acknowledged that seismic isolation could play a role in addressing this cost driver. Section 6.5.2 states that potential savings from seismic isolation are not assumed or further discussed in this analysis because EPRI has other ongoing research projects focused on this area.

Table 7-2
Effect of Modularization on Cost. Courtesy of Maronati. (Adapted from Maronati 2018)

Degree of Modularization	Strategy 1	Strategy 2	Strategy 3
Base Cost (BC)	0.44 (-36.74%)	0.63 (-10.61%)	0.70
Overnight Construction Cost (OCC)	0.61 (-29.82)	0.79 (-8.61%)	0.87
Total Capital Investment Cost (TCIC)	0.70 (-29.95)	0.91 (-8.26%)	1.00

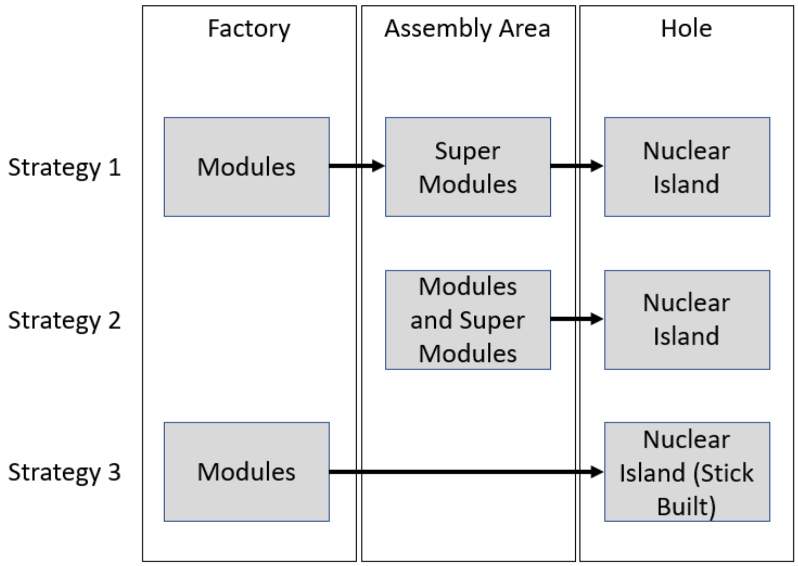

Figure 7-1
Three Different Construction Strategies Using Degrees of Modularity. Courtesy of Maronati (Adapted from Maronati 2018)

7.1.3 Baseline Constructability of Design

The constructability of a design is the degree to which obstacles faced during construction are foreseen and avoided during the design phase. These pre-build design changes will minimize the need to demolish, redesign, and rebuild plant features during construction. It will avoid costly delays that result from design changes during construction, which could impact the licensing basis, and it will decrease the cost of construction, maintenance, operation, and inspections.

Although designing for constructability requires additional investment when designing the first plant, it will decrease the cost of NOAK units. Additional design work prior to beginning construction is expected to minimize redesigning safety related systems during construction which avoids schedule and regulatory delays. This investment will help avoid some cost overruns in FOAK plants.

Designing for constructability may be accomplished using artificial intelligence to redesign features from the bottom-up. Other industries have had success through the use of Building Information Modeling (BIM), an intelligent building planning tool which allows designers to see how design decisions affect adjacent systems, structures, and components.

EEDB Phase IX identifies specific percentage savings for the IPWR12, in each of the two-digit code of accounts relative to PWR12ME. For some of the COA discussed below, these specific numbers were used. In other cases, the aggregate reduction in direct costs (linear combination of savings from COA 21 through 26) or the aggregated reduction in indirect costs (linear combination of savings from EMWG COA 91 through 93) were used. (Note that the EMWG G4-ECONS COA designates indirect as 3 series as opposed to 9 series COAs as is used in the EMWG reports.)

The aggregate direct cost reductions were a 20.5% reduction in site labor costs, 8.7% reduction in site material costs, and a 2.8% increase in factory equipment costs. The aggregate indirect cost reductions were a 19.9% reduction in site labor costs, 14.6% reduction in site material costs, and a 49.7% reduction in professional services for an overall 35.5% reduction in $/kWe. In general, the EEDB IPWR improvements were seen as a technically robust benchmark, generally applicable to most COAs. In some identified circumstances, other references and estimates were used.

Designing for constructability is expected to affect the following COA in NOAK plants (note indirect costs are identified by their G4-ECONS 3X designation).

- Design services offsite (COA 35) – It is estimated that 75% of offsite design services during construction are spent dealing with construction issues, which can be minimized through a better design for constructability. The balance is spent dealing with errors in the design and are assumed to be a baseline cost that may be improved as additional plants are built but never fully eliminated. The aggregate indirect cost improvement factor of 35.5% was assumed for this COA.
- Construction supervision (COA 32) – It is estimated that 25% of construction supervision costs can be attributed to designing during construction. The aggregate indirect cost improvement factor of 35.5% was assumed for this COA.
- Project/construction management services onsite (COA 38) – It is estimated that 25% of onsite management costs can be attributed to designing during construction. The aggregate indirect cost improvement factor of 35.5% was assumed for this COA.
- Structures and improvements (COA 21) – The cost of some of the structures within COA 21 could be reduced by designing for constructability. These are generally structures made by craftsman on site and not site improvements such as paving which are performed by the lowest bidder. EEDB Phase IX (DOE 1987) estimated a 6.3% reduction in $/kWe for this category. This reduction is lower than what was assumed for other COA because EEDB IX applied the savings expected from modularity the auxiliary building but not the other structures. In this analysis, the aggregate cost savings were assumed to be applicable to the three-digit COA identified in Table 7-3. In total, it was estimated that 91% of the COA 21 were affected by this cost driver. It is further noted that additional savings can be found in the 10 series COA (Preconstruction Activities), however these are small and likely location specific. For example, in some instances, remote siting may reduce land costs. The aggregate direct cost improvement factor of 15% (20.5% reduction in site labor costs, 8.7% reduction in site material costs, and a 2.8% increase in factory equipment costs) were applied to 91% of this COA identified in Table 7-3.

- Reactor equipment (COA 22) – The NSSS is fully designed prior to construction and does not change significantly along the learning curve. COA 224 contains the radiation waste processing structure. Some sites are able to nearly completely eliminate their facilities and perform the waste processing offsite. It is assumed this would represent a 90% cost reduction for the 10% of this COA attributed to waste processing.
- Turbine Plant Equipment (COA 23) – COA 23 includes the turbine as well as the turbine pedestal. It is estimated that designing for constructability could significantly reduce the cost of pedestal. EEDB provides an overall improvement factor of 6.3% for the entire COA.
- Electrical tunnels (COA 24) – The cost of laying electrical cables can be significantly improved through better design and construction planning. Roughly 17.5% of the cost of electrical tunnels is labor and can be reduced by better design. It is estimated that the cost of electrical tunnel labor can be reduced by 50% through better construction planning.

7.1.4 Material Costs

The EEDB estimates that total construction activities will require 4.35×10^6 ft^3 (1.23×10^5 m^3) of concrete, 2.13×10^6 ft^2 (1.98×10^5 m^2) of formwork, 1.54×10^5 ft^3 (4.36×10^3 m^3) of steel, 1.11×10^7 lbm (5.03×10^6 kg) of piping, and 7.14×10^6 ft (2.18×10^6 m) of wiring (DOE 1987). In total, these materials cost roughly $375/kW or 7% of the cost of a new plant. Figure 7-2 and Figure 7-3 illustrate the fraction of the total cost that is due to materials. Some of the cost saving technologies that can reduce the quantity of materials needed are listed below.

- High performance materials, such as high-strength reinforcing steel
- Increase appropriate use of advanced manufacturing and welding
- Develop smart formwork for concrete
- Develop smart batch plant for concrete
- Develop method to test the concrete prior to loading it in the truck

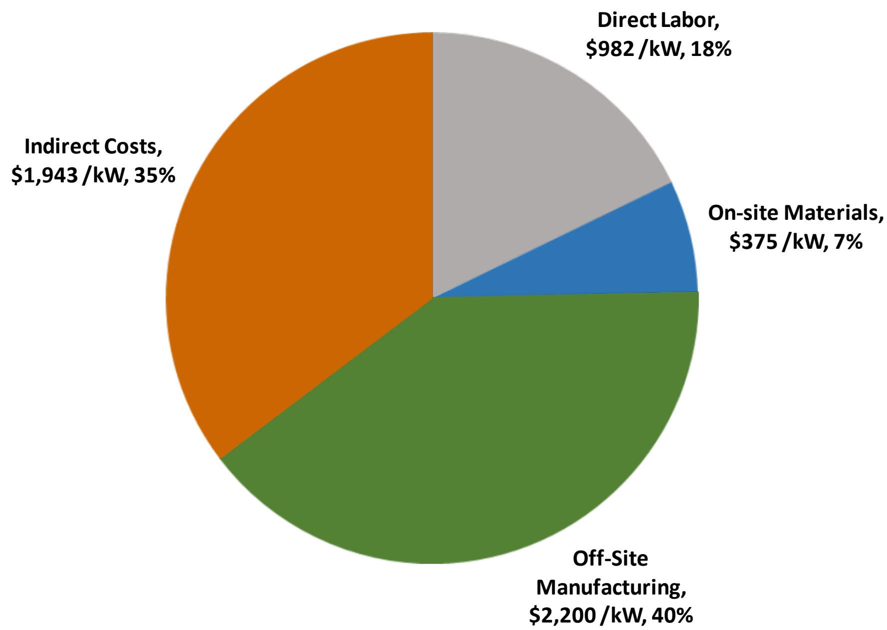

Figure 7-2
Fraction of OCC Associated with Indirect Costs, Site Materials, Site Labor Cost, and Off-Site Manufacturing

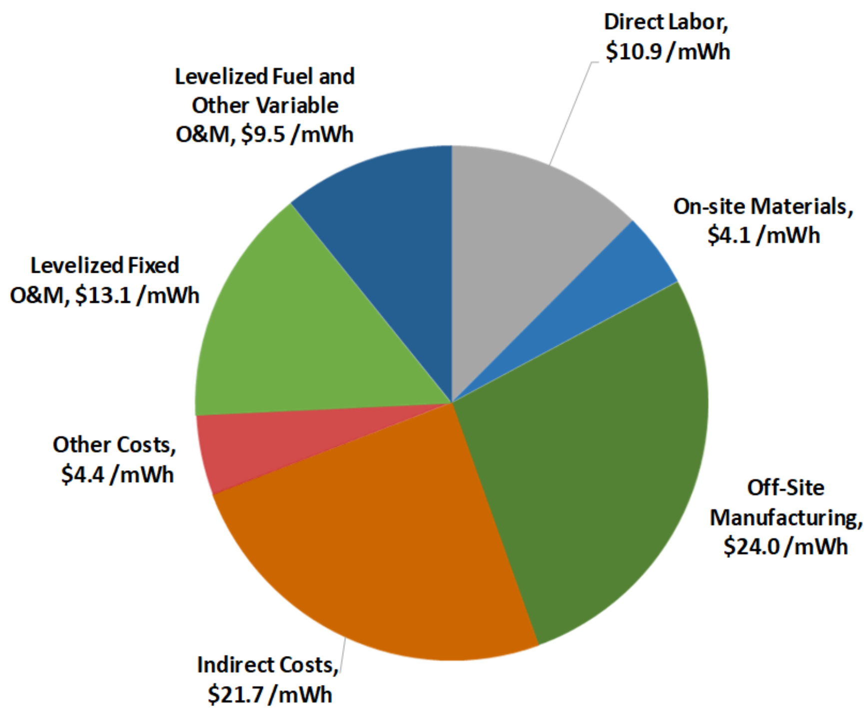

Figure 7-3
Fraction of LCOE Associated with Indirect Costs, Other Costs, On-Site Materials, Site Labor Cost, and Off-Site Manufacturing

7.1.5 Inspection (QA/QC) Delays

Forty percent of craft laborers surveyed in the late 1970s, at six different nuclear power plants under construction in U.S., listed quality control inspection delays as a substantial issue (Borcherding 1980). These workers reported an average delay of 1.47, 2.50, and 3.90 MH per craftsman per week for carpenters, electricians, and pipefitters. The overall estimate was 2.61 MH per individual on a weekly basis. The surveyed craftsmen reported that the inspectors were typically available when they were needed and that the primary reason for delays were interpreting the plans and specifications provided by examiners.

Advancements could be made to reduce or eliminate some inspections. Some possibilities could include:

- Automate the inspection and qualification of concrete.
- Develop continual or near-real-time inspections of material and member placement (deployment can be through laser, drone, scanner, etc.).
- Automate the development of as-built drawings/conditions.
- Increase appropriate use of sensors (including for concrete placement).
- Increase appropriate use of automated monitoring/control.
- Increase appropriate use of advanced Nondestructive Examination (NDE) (e.g., Ground Penetrating Radar (GPR), Ultrasonic Testing (UT), other).
- Develop a rationale for fewer inspections.

If the time spent on inspections could be reduced, 90% of 2.61 MH per week could be reduced. This would result in a decrease in the cost of labor and the construction time by 5.8%.

7.1.6 Reliance Upon Consensus Based Codes and Standards

Designers hoping to use advanced materials and technologies must wait for consensus from code, standards, and specification committees. However, these documents are usually slow to produce because they are consensus-based in order to better ensure high-quality, unbiased documents. Changes to this process for developing documents written in mandatory language and used by the nuclear power industry could allow for swifter turnaround and will support adoption by regulators, designers, and constructors within the nuclear power industry. Possible ideas include:

- Using risk-informed guidance on use of code in-lieu of rulemaking.
- Incentivize resources to develop standards.
- Increase collaboration among multiple code committees.
- Improve pathway for NRC (or other regulator) acceptance without waiting for a specific code case upon which the design or construction activity depends.

7.1.7 Excessive Margin

There are numerous instances in the plant designs where conservatisms are stacked, leading to what some experts believe to be excessive margin. This is especially true for civil/structural structures with seismic requirements and with regard to radiation protection (i.e., the LNT model assumption). Modeling research could be completed, in order to identify instances in which these margins are unnecessary and could be reduced. However, prior to the completion of the modeling, it is unknown what savings might be realized by reducing these margins.

7.1.8 Non-Severability of Design Features

When safety related systems or non-safety related systems adjacent to safety related systems must be redesigned during construction, the results are significant delays and costs due to the relicensing process. These delays and costs are one principal reason for the cost overruns and delays in the construction of FOAK plants. Although it is assumed that the redesign of safety related systems will not be necessary for NOAK units, reducing the connections between safety related and non-safety related systems has the potential to significantly reduce any possible delays, resulting in a more certain costs of nuclear construction. This will increase investor optimism, increasing the likelihood of future projects and decreasing the required rate of return on borrowed money.

7.1.9 Regulatory Requirements

The cost of regulation is observed by noting the significant cost differences between nuclear grade components and similar components used in fossil plants. While in some cases, the nuclear grade components and materials provide superior value, in other cases, industry experts believe that the existing requirements are unnecessary. Some of them could be removed, making the licensing process cheaper and possibly reducing OCC.

7.1.10 Supply Chain Issues

It has been many years since nuclear power plants have been built in the United States at a rate sufficient to maintain a supply chain for nuclear grade components. There are a number of options for how this issue could be remedied.

- Development of a full supply chain will require confidence by suppliers that multiple new nuclear power plants will be built. Suppliers may be incentivized to begin investing in nuclear-specific technologies if some initial investment or demonstration was independently funded.
- The effect of this cost driver could be reduced by reducing the number of quality-controlled components. This would require regulatory changes, but work could be completed to demonstrate that off-the-shelf non-nuclear grade components perform on a comparable level to those produced with proper QA/QC. It could also mean expanding the use of commercial grade dedication.
- The barrier to entry for suppliers to become nuclear grade suppliers could be lowered. As with the last point, this would require regulatory changes.

The extent to which these solutions could affect the LCOE from nuclear power depends on the extent to which suppliers and regulators are willing to change. In an attempt to make nuclear power more cost-effective, regulators could make sweeping changes to lower the barrier to entry for new suppliers. It is also possible that a political commitment to carbon-free technologies will incentivize the investments in the resources to needed to develop nuclear quality product lines.

7.1.11 Unknown Risks

Recent domestic nuclear power plant construction projects have included schedule delays and cost overruns. These delays are related to inspection (discussed in Section 7.1.5), possible redesign of safety related systems or non-safety related systems adjacent to safety related systems (discussed in Section 7.1.8), and a host of other factors. Some delays could be foreseen and managed in a more time and cost-efficient manner, if more project planning was completed prior to the beginning of construction. This is demonstrated by Figure 6-2 which shows that total capital costs decrease as more of the design is completed. Incompatibilities and inconsistences can be found and remedied before resources are mobilized. In some cases, it can prevent building and then demolishing structures with design interferences. BIM and other modeling software can be used in the design process to foresee interferences.

Other risks are truly unknown and require project planners to have flexible solutions and address the cost drivers as they arise with minimal schedule impact. Additive manufacturing has been used with success in naval reactors where it is sometimes impractical or impossible to ship spare parts when they are needed. It may also be useful on a construction site to decrease the wait time needed for components and be able to respond to design changes more quickly. Additive manufacturing can be also be used for rapid prototyping or building full scale components out of less costly materials. This is useful for demonstrating clearances, training workers, and ensuring that pieces fit together as expected. In many cases, rapid prototyping does not have a positive value proposition, but for sensitive components, training with full-scale pieces can avoid unknown risks.

7.1.12 Workforce Training (Qualifications)

The unavailability of qualified workers has been identified as one inefficiency that leads to schedule delays. Inexperienced workers make mistakes, misunderstand directions, and complete their assignments slower than other qualified workers. Workforce training could be one possible solution. This is particularly relevant for inspectors who must understand the directions provided to them and recognize off-normal conditions. Since many inspections are completed in-place, inspector training could reduce construction duration and decrease indirect costs.

7.2 Model Results

This section summarizes results from the nuclear cost model developed for this study. The model incorporates quantitative assessments of potential cost reductions from five of the cost drivers described above:

1. Craft Labor Costs
2. Civil/structural design
3. Constructability of design

4. Materials
5. Inspection (QA/QC)

For each of these cost driver categories, the model identifies the relevant COAs along with their baseline cost estimates. As part of establishing the baseline effects of the cost drivers on relevant COAs, the model also incorporates estimated percentages of the relevant COA cost values directly affected by the cost drivers. After establishing the baseline effects of the five cost drivers by COA, the model then uses estimates for the potential savings from specific cost driver strategies (described above) as percentages of the baseline values to calculate reductions. The methodology for identifying affected COAs and estimating potential savings, combines reviews of the Phase IX EEDB report comparing the IPWR with PWR12ME as described above, discussions from the EPRI/GAIN/NEI workshop meeting, and engineering judgment.

The next subsection provides details on the baseline capital costs and the levelized cost of electricity (LCOE), using input parameter assumptions from authoritative sources. The subsequent section presents the potential reductions in capital costs and LCOE from implementing the cost driver strategies.

7.2.1 Baseline Total Capital Costs and LCOE

As discussed in Section 5, this analysis uses the PWR12ME from the EEDB Phase IX report issued by the U.S. Department of Energy in 1987, as the reference point for baseline cost values. Inflating 1987 dollars in that report to contemporary currency leads to capital costs of $5500/kWe for direct and indirect cost components.

Calculating the baseline LCOE (defined in Section 3.4) entails calculating the total capital cost, including interest during construction and other adders. The model estimates interest during construction to be $1283/kWe based on a construction schedule of 72 months, and at an interest rate of 7% (assumption from Section 6.4.2). Other additions, representing pre-construction costs, owner’s costs, and supplemental costs, collectively represent $428/kWe. The total capital cost (TCIC, defined in Section 3.3) then becomes $7211/kWe.

The three additional input parameters for leveling total capital cost are discount rate (for bringing future revenues to a present value), time period, and the annual capacity factor, and are adjustable in the model. Baseline calculations use a 7% discount rate and 60-year plant life time (IAEA 2015). For consistency with U.S. nuclear operations, baseline calculations use a 90% capacity factor (U.S. EIA 2019). With these parameters, the baseline levelized capital cost is $65/MWh.

The remaining parameters for calculating LCOE, relate to the operating and maintenance (O&M) costs ($13/MWh, discussed in Section 6.4.10) and fuel cost ($10/MWh, discussed in Section 6.4.5). Summing these O&M components with the levelized capital cost yields an LCOE of $88/MWh for the baseline model calculations[3].

[3] Other estimates range from about $77/MWh (EIA 2019, based on $5300/kWe OCC) to $120/MWh (Lazard 2016, based on a OCC of $12,000/kWe).

7.2.2 COAs and Baseline Costs Affected by Selected Cost Drivers

Table 7-4 shows COAs and baseline costs affected by the five cost drivers included in this modeling analysis: (1) craft labor costs, (2) civil/structural design, (3) constructability of design, (4) materials, and (5) inspection (QA/QC).

In the design of this analysis, these five cost drivers are neither mutually exclusive nor collectively comprehensive. As a result, some COAs appear on multiple rows of the table because they are affected by multiple cost drivers, and many COAs are not included because they are not affected by these cost drivers. For these reasons, summing the baseline costs affected by the cost drivers would not yield the baseline cost for the reference nuclear plant ($5500/kW). Moreover, summing the estimates of potential cost reductions from the drivers, which are shown in the next subsection, would not yield the total potential cost reduction from implementing all the strategies, because some COAs would be double counted and there would be interaction effects among the multiple strategies. This is further discussed in Section 7.2.4.

The first column of Table 7-4 shows the account numbers, with 20s related to direct construction costs and 30s related to indirect services. In the full cost accounting system, direct construction costs by COA are subdivided into equipment, materials, and labor. The third column of the table uses abbreviations to denote whether the affected costs represent the total for the COA or one of the subdivisions. The fourth column shows the relevant component's baseline cost estimate.

The fifth column in the table (second from the right) expresses the percentage of each cost component that is affected by the cost driver. This is necessary because in many cases, the cost drivers affect only part of the COAs. The rational for these values is presented in Section 7.1. The sixth column is the fourth column (baseline COA) multiplied by the fifth column (affected percentage).

As an example, the first block relates to the constructability of design, and the first cost component listed in Table 7-4 on row 21: Structures and improvements. In the table, this row has "T" in the third column because its total baseline costs serve as point of departure (rather than equipment, materials, or labor subdivision). The total baseline cost for COA 21 is $1385/kWe based on the modeling approach described above. Section 7.1.3 explains that 91% of this cost component is affected by constructability of design; the other 9% is unaffected by it. Thus, the baseline contribution of constructability of design is $1260/kW, as shown in the sixth column. Other rows in the table are calculated in the same manner.

Table 7-3
COA and Baseline Costs Affected by Selected Cost Drivers

Step 1: Understanding Cost Driver Constributions Toward Baseline $5,500/kW Nuclear					
Baseline Cost Drivers and Relevant Cost Codes[1]			Full Baseline Cost for Code	% Affected by Cost Driver[2]	Baseline Cost Contributions
Craft Labor Costs					**$2,925/kW**
21	Structures and Improvements	L	$565/kW	100%	$565/kW
22	Reactor Equipment	L	$123/kW	100%	$123/kW
23	Turbine Generator Equipment	L	$64/kW	100%	$64/kW
24	Electrical Equipment	L	$51/kW	100%	$51/kW
25	Heat Rejection System	L	$77/kW	100%	$77/kW
26	Miscellaneous Equipment	L	$102/kW	100%	$102/kW
	Indirect Costs	T	$1,943/kW	100%	$1,943/kW
Civil/Structural Design					**$3,318/kW**
21	Structures and Improvements	T	$1,385/kW	91%	$1,260/kW
23	Turbine Generator Equipment	T	$384/kW	30%	$115/kW
	Indirect Costs	T	$1,943/kW	100%	$1,943/kW
Constructability of Design					**$2,338/kW**
21	Structures and Improvements	T	$1,385/kW	91%	$1,260/kW
22	Reactor Equipment	T	$858/kW	10%	$86/kW
23	Turbine Generator Equipment	T	$384/kW	100%	$384/kW
24	Electrical Equipment	T	$291/kW	50%	$146/kW
32	Construction supervision	T	$237/kW	25%	$59/kW
35	Design services offsite	T	$389/kW	75%	$292/kW
38	Project/constr mgmt services onsite	T	$223/kW	50%	$112/kW
Materials					**$907/kW**
21	Structures and Improvements	M	$170/kW	100%	$170/kW
21	Structures and Improvements	L	$565/kW	50%	$282/kW
22	Reactor Equipment	M	$35/kW	100%	$35/kW
23	Turbine Generator Equipment	M	$20/kW	100%	$20/kW
24	Electrical Equipment	M	$40/kW	100%	$40/kW
25	Heat Rejection System	M	$10/kW	100%	$10/kW
26	Miscellaneous Equipment	M	$100/kW	100%	$100/kW
31	Field indirect costs	M	$250/kW	100%	$250/kW
Inspection (QA/QC)					**$302/kW**
21	Structures and Improvements	L	$565/kW	25%	$141/kW
22	Reactor Equipment	L	$123/kW	25%	$31/kW
32	Construction supervision	T	$237/kW	50%	$118/kW
33	Commissioning and startup costs	T	$24/kW	50%	$12/kW

Notes: 1) In the third column, "T" denotes total costs within the COA, "E" denotes the equipment component of the COA, "M" denotes the materials component, and "L" denotes the labor component.
2) References provided in Section 7.

7.2.3 Potential Cost Savings from Cost Driver Strategies

Table 7-5 presents the estimated cost savings from implementing the driver strategies described above. The left side reproduces the baseline cost effects from the drivers documented in the previous table. The right side shows the two columns of values to calculate the potential cost savings.

The second-to-last column indicates the estimated percentage reduction in each cost component row’s baseline driver effect from implementing strategies (the assumptions for these values are presented in Section 7.1). The last column in the table indicates the resulting cost savings estimate from multiplying the baseline cost effect by the potential reduction percentage. Figure 7-4 provides a summary of the cost drivers and the potential savings from each.

For example, the calculation of potential cost savings for the first cost component row (21: Structures and Improvements) uses an estimate of 15% reduction, derived from the approach described in the previous paragraph, from the baseline cost contribution for constructability of design. With the baseline cost contribution of $1260/kWe for this row, a 15% reduction would lead to cost savings of $189/kWe. Other rows in the table are calculated in the same manner.

The values in bold in the last column give the total estimated cost savings from implementing each driver strategy.

Table 7-4
Estimated Cost Savings from Driver Strategies

Step 1: Understanding Cost Driver Constributions Toward Baseline $5,500/kW Nuclear						Step 2: Evaluating Potential	
Baseline Cost Drivers and Relevant Cost Codes[1]			Full Baseline Cost for Code	% Affected by Cost Driver[2]	Baseline Cost Contributions	% Reduction from Baseline Contrib.[2]	Potential Cost Savings
Craft Labor Costs					**$2,925/kW**		**$948/kW**
21	Structures and Improvements	L	$565/kW	100%	$565/kW	50%	$282/kW
22	Reactor Equipment	L	$123/kW	100%	$123/kW	50%	$62/kW
23	Turbine Generator Equipment	L	$64/kW	100%	$64/kW	50%	$32/kW
24	Electrical Equipment	L	$51/kW	100%	$51/kW	50%	$26/kW
25	Heat Rejection System	L	$77/kW	100%	$77/kW	50%	$38/kW
26	Miscellaneous Equipment	L	$102/kW	100%	$102/kW	50%	$51/kW
	Indirect Costs	T	$1,943/kW	100%	$1,943/kW	24%	$456/kW
Civil/Structural Design					**$3,318/kW**		**$892/kW**
21	Structures and Improvements	T	$1,385/kW	91%	$1,260/kW	30%	$378/kW
23	Turbine Generator Equipment	T	$384/kW	30%	$115/kW	50%	$58/kW
	Indirect Costs	T	$1,943/kW	100%	$1,943/kW	24%	$456/kW
Constructability of Design					**$2,338/kW**		**$503/kW**
21	Structures and Improvements	T	$1,385/kW	91%	$1,260/kW	15%	$189/kW
22	Reactor Equipment	T	$858/kW	10%	$86/kW	90%	$77/kW
23	Turbine Generator Equipment	T	$384/kW	100%	$384/kW	6%	$24/kW
24	Electrical Equipment	T	$291/kW	50%	$146/kW	35%	$51/kW
32	Construction supervision	T	$237/kW	25%	$59/kW	35%	$21/kW
35	Design services offsite	T	$389/kW	75%	$292/kW	35%	$102/kW
38	Project/constr mgmt services onsite	T	$223/kW	50%	$112/kW	35%	$39/kW
Materials					**$907/kW**		**$383/kW**
21	Structures and Improvements	M	$170/kW	100%	$170/kW	50%	$85/kW
21	Structures and Improvements	L	$565/kW	50%	$282/kW	25%	$71/kW
22	Reactor Equipment	M	$35/kW	100%	$35/kW	50%	$18/kW
23	Turbine Generator Equipment	M	$20/kW	100%	$20/kW	50%	$10/kW
24	Electrical Equipment	M	$40/kW	100%	$40/kW	50%	$20/kW
25	Heat Rejection System	M	$10/kW	100%	$10/kW	50%	$5/kW
26	Miscellaneous Equipment	M	$100/kW	100%	$100/kW	50%	$50/kW
31	Field indirect costs	M	$250/kW	100%	$250/kW	50%	$125/kW
Inspection (QA/QC)					**$302/kW**		**$151/kW**
21	Structures and Improvements	L	$565/kW	25%	$141/kW	50%	$71/kW
22	Reactor Equipment	L	$123/kW	25%	$31/kW	50%	$15/kW
32	Construction supervision	T	$237/kW	50%	$118/kW	50%	$59/kW
33	Commissioning and startup costs	T	$24/kW	50%	$12/kW	50%	$6/kW

Notes: 1) In the third column, “T” denotes total costs within the COA, “E” denotes the equipment component of the COA, “M” denotes the materials component, and “L” denotes the labor component.
2) References provided in Section 7.

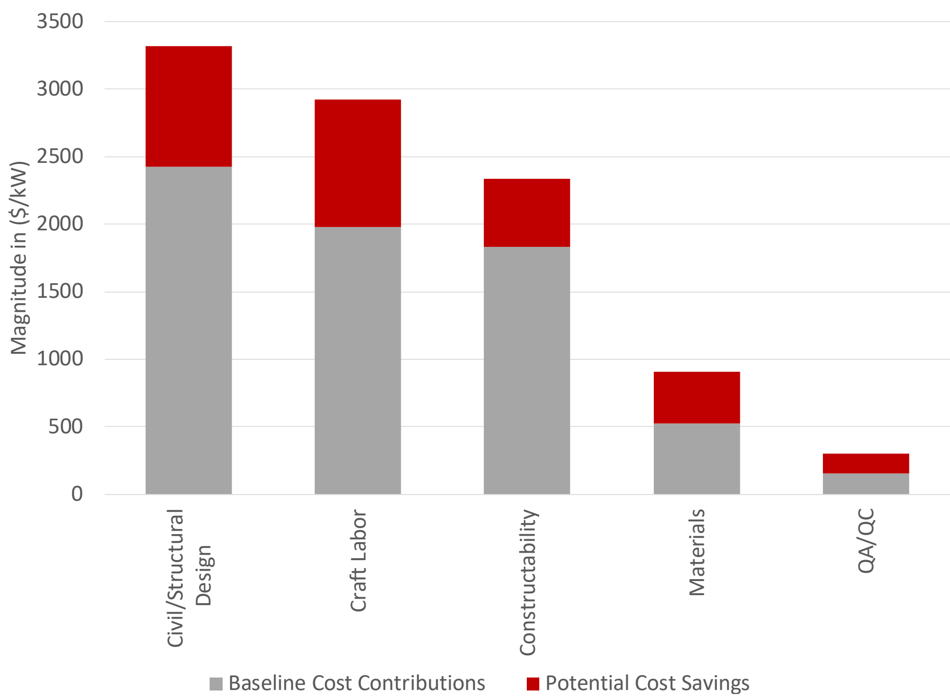

Figure 7-4
Summary of Cost Drivers and Potential Savings

7.2.4 Addressing All Cost Drivers

As stated previously, the cost drivers have some overlap. For the purposes of estimating the total benefit that could be realized if all cost reduction strategies were used, some of the benefits for individual cost drivers were subtracted from the total, in order to avoid double counting. It is assumed that the benefits from materials, craft labor costs, and inspection (QA/QC) are sufficiently unique.

Some of the benefits listed under constructability of design and civil/structural design were also removed when summing all the cost drivers together, because the improvements were already covered by other drivers. Those instances are described below.

- Structures and Improvements (21) was affected by each cost driver. The benefits listed under constructability of design were considered redundant to those listed in other categories ($189/kW).
- Indirect cost savings related to reductions in schedule were listed under civil/structural design and craft labor costs. This benefit was counted only once ($456/kW).
- Reactor equipment (22), turbine generator equipment (23), and electrical equipment (24) are included in constructability, materials, and craft labor costs. The benefits listed under constructability of design were considered redundant to those listed in other categories ($77/kW, $24/kW, and $51/kW, respectively).

To avoid double counting, a total of $798/kW was subtracted from the total potential savings if all the cost drivers are addressed at once. This leaves an opportunity for a cost reduction of $2079/kW from the existing baseline OCC of $5500/kW, **resulting in a potential OCC cost of $3421/kW**.

Additional savings could be achieved by addressing the cost drivers for which a quantitative analysis was not done, assuming more aggressive cost reductions for the analyzed cost-drivers, or assuming that schedule reductions from reduced craft labor costs (increases in worker productivity) and improved civil/structural design are not mutually exclusive.

7.2.5 Summary of OCC and LCOE Cost Reductions by Cost Driver Category

Figure 7-5 summarizes the potential cost savings calculated in the project, by cost drivers. As discussed earlier, it is difficult to sum each of the individual cost savings to arrive at a total cost savings potential, due to the overlap in the way the cost savings were calculated.

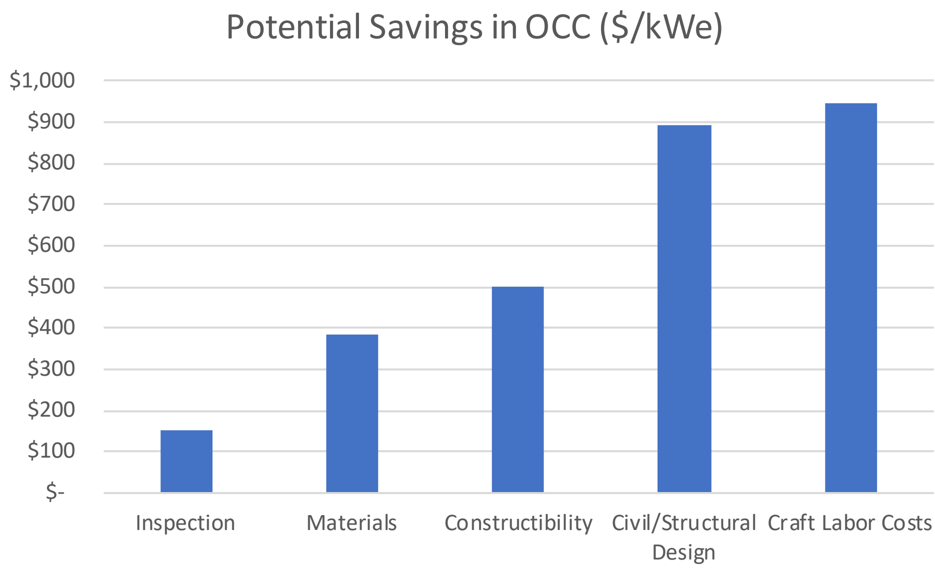

Figure 7-5
Summary in Potential Reduction in OCC for Each Cost Driver Opportunity

As for LCOE, an estimate of potential reductions can be made by assuming OCC represents about 60% of the $88/MWh baseline LCOE value. Strictly speaking, for each cost driver one would need to independently calculate the construction schedule time associated with the cost driver opportunity on IDC. But assuming the contribution to construction schedule are proportional to savings in OCC, Figure 7-6 illustrates potential reductions in LCOE for each opportunity.

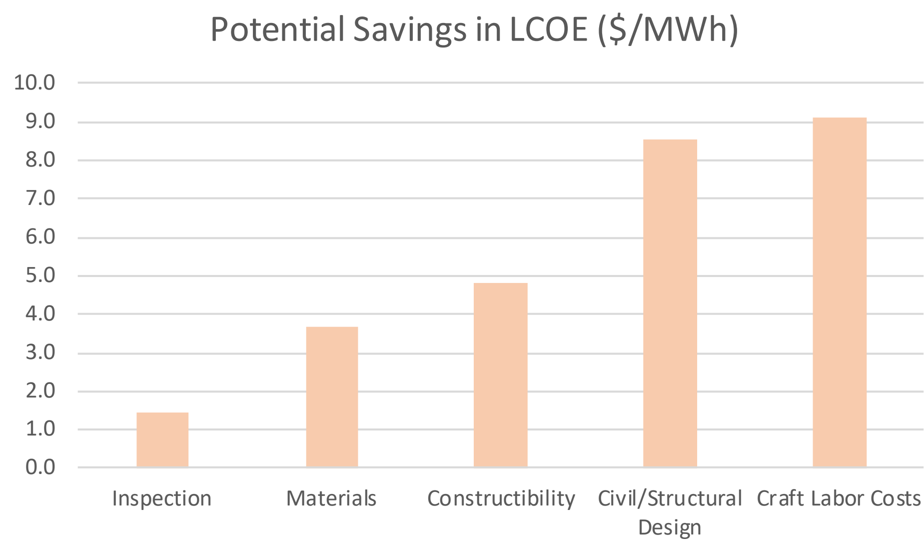

Figure 7-6
Summary in Potential Reduction in LCOE for Each Cost Driver Opportunity

7.3 Evaluation of Technology Types

There are many possible projects that can reduce costs of NOAK plants. To demonstrate how this tool could be used to assess the saving from implementation of a variety of technologies, six general categories were defined based on the primary way the technology reduces cost. These groups are not meant to be exclusive because many projects are able to significantly reduce costs across multiple categories.

For each of these technology types, a generic technology was evaluated to illustrate the potential cost savings that could be achieved through the implementation of the technology. Because cost savings projections of this type are not generally available for all projects under consideration, it is not possible to provide such an assessment for every project. The generic examples given in the following sections provide guidance for evaluating specific projects, including those that have not yet been identified. Specific examples of technologies are identified in Table 7-18. This table also lists which cost drivers the technologies address, how they influence OCC and LCOE, the timeframe over which they may be deployed, the kind of plant design that could benefit from it, and estimated magnitude of the effect they could have.

7.3.1 Advanced Materials

The advanced materials group contains materials that are stronger, lighter, or in some way perform better than other comparable materials that are traditionally used. The use of advanced materials often results in a net decrease in cost (via reduced cost of on-site materials) although sometimes working with these materials is more difficult (increasing labor costs) or requires more preparation off site (increasing off-site material costs). Conversely, some advanced materials are costlier but achieve savings through reduced labor or reduced schedule (see Section 7.3.2.). Material costs are identified as a cost driver in Section 7.1.4. Some examples of these technologies include high strength reinforcing steel, mechanical splicing of reinforcement, optimization of concrete placements, and code acceptance of existing advanced materials. Some of these ideas are listed in Table 7-17.

For example, advanced material could provide 10% savings on materials and 5% savings on labor across the Structures and Improvements COA (mostly concrete structures). If successfully implemented this technology could reduce OCC of the plant by $62.2/kW and LCOE by $0.7/MWh. The inputs and results of this calculation are provided in Table 7-6, Table 7-7, Figure 7-7, and Figure 7-8. The results were rounded to the significant digit.

Table 7-5
OCC Savings from Example Technology 1 (Advanced Materials)

COA	Labor	Materials	Equipment	Labor	Materials	Equipment	Total Savings
Structures and Improvements (21)	-5%	-10%	0%	$28.2/kW	$34.0/kW	$0.0/kW	$62.2/kW
Indirect Costs (3X)	0%			$0.0/kW			$0.0/kW
Total OCC Savings for Example Technology 1 (Advanced Materials)							**$62.2/kW**

Table 7-6
LCOE Savings from Example Technology 1 (Advanced Materials)

COA	Labor	Materials	Equipment	Labor	Materials	Equipment	Total Savings
Structures and Improvements (21)	-3%	0%	0%	$0.3/MWh	$0.4/MWh	$0.0/MWh	$0.7/MWh
Indirect Costs (3X)	0%			$0.0/MWh			$0.0/MWH
Total LCOE Savings for Example Technology 1 (Advanced Materials)							**$0.7/MWh**

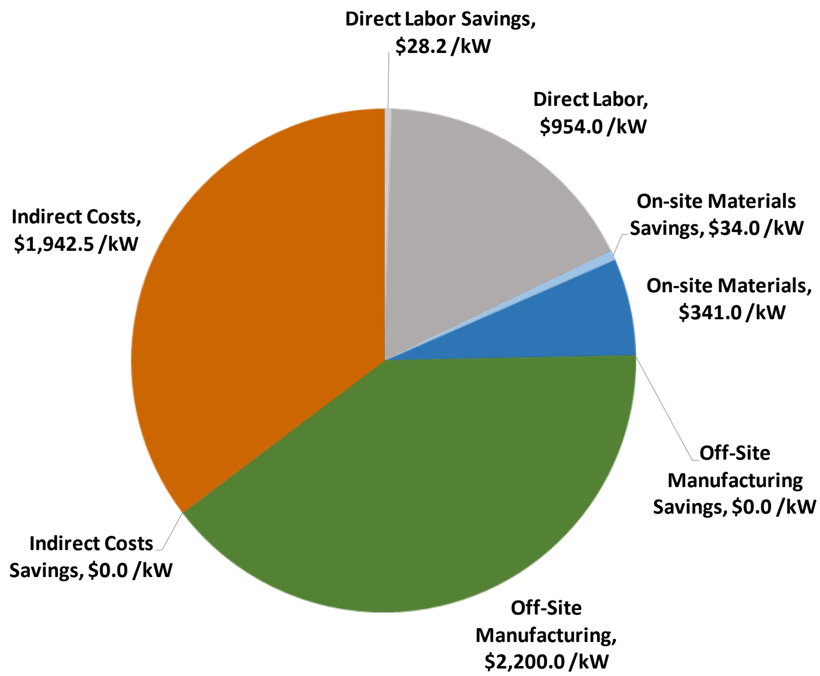

Figure 7-7
OCC Savings from Example Technology 1 (Advanced Materials)

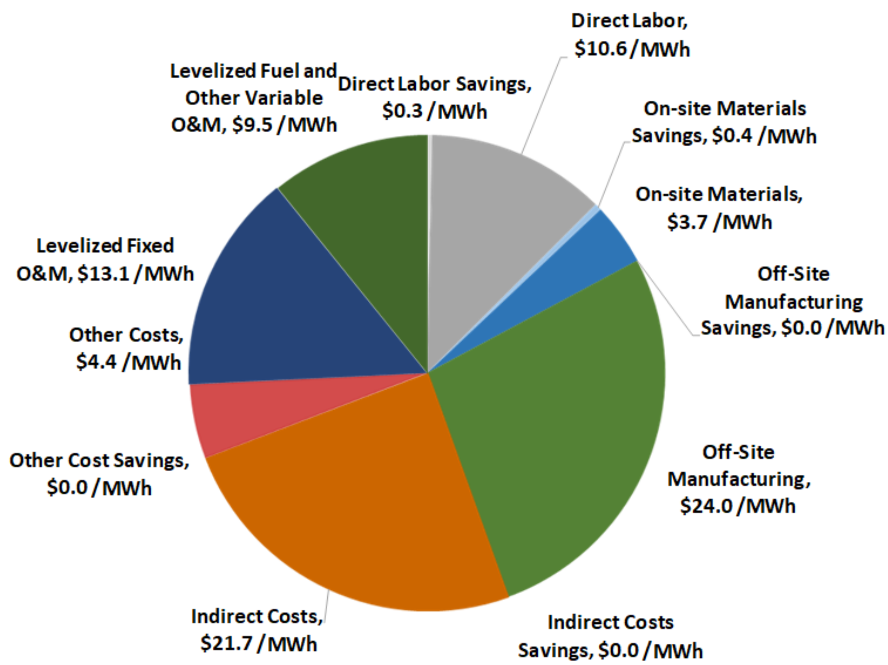

Figure 7-8
LCOE Savings from Example Technology 1 (Advanced Materials)

7.3.2 Construction Methods or Materials that Reduce Craft Labor Costs

A number of materials and construction techniques have been developed to make the structures and components easier to install. These practices or materials result in decreased on-site labor costs, although their use sometimes requires additional spending on materials or on off-site manufacturing.

Because these technologies reduce labor hours, they may also reduce construction duration, which provides significant saving of indirect costs. Technologies in this group primarily address the cost driver discussed in Sections 7.1.1, 7.1.5, and 7.1.12. Some example technologies are enhanced concrete formwork technologies, improved welding technologies, self-consolidating concrete, moisture tolerant coatings, advanced concrete, tools that increase inspect-ability, embedded sensors, advanced NDE, surface mounted seismic sensors, and use of robotics. Some of these ideas are listed in Table 7-18.

An example construction method could result in a decrease for all labor and provide 20% savings on labor and 5% savings on materials across the structures and improvements COA (mostly concrete structures). If successfully implemented this technology could reduce OCC by $121.4/kW and LCOE by $1.4/MWh. The inputs and results of this calculation are provided in Table 7-8, Table 7-9, Figure 7-9, and Figure 7-10.

Table 7-7
OCC Savings from Example Technology 2 (Construction Method – Labor Reduction)

COA	Labor	Materials	Equipment	Labor	Materials	Equipment	Total Savings
Structures and Improvements (21)	-20%	-5%	0%	$112.9/kW	$8.5/kW	$0.0/kW	$121.4/kW
Indirect Costs (3X)	0.0%			$0.0/kW			$0.0/kW
Total OCC Savings for Example Technology 2 (Construction Method – Labor Reduction)							**$121.4/kW**

Table 7-8
LCOE Savings from Example Technology 2 (Construction Method – Labor Reduction)

COA	Labor	Materials	Equipment	Labor	Materials	Equipment	Total Savings
Structures and Improvements (21)	-14%	0%	0%	$1.3/MWh	$0.1/MWh	$0.0/MWh	$1.4/MWh
Indirect Costs (3X)	0%			$0.0/MWh			$0.0/MWh
Total LCOE Savings for Example Technology 2 (Construction Method – Labor Reduction)							**$1.4/MWh**

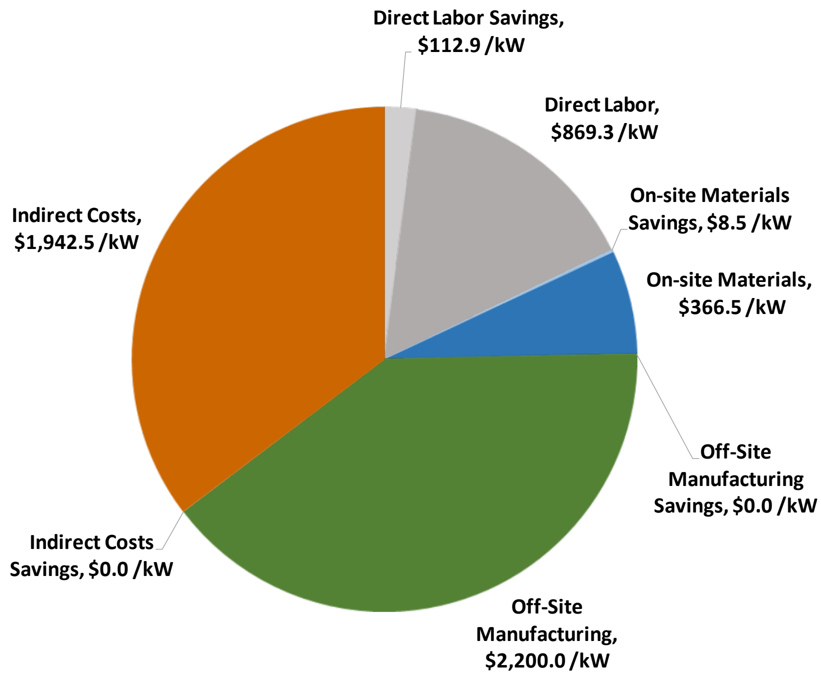

Figure 7-9
OCC Savings from Example Technology 2 (Construction Method – Labor Reduction)

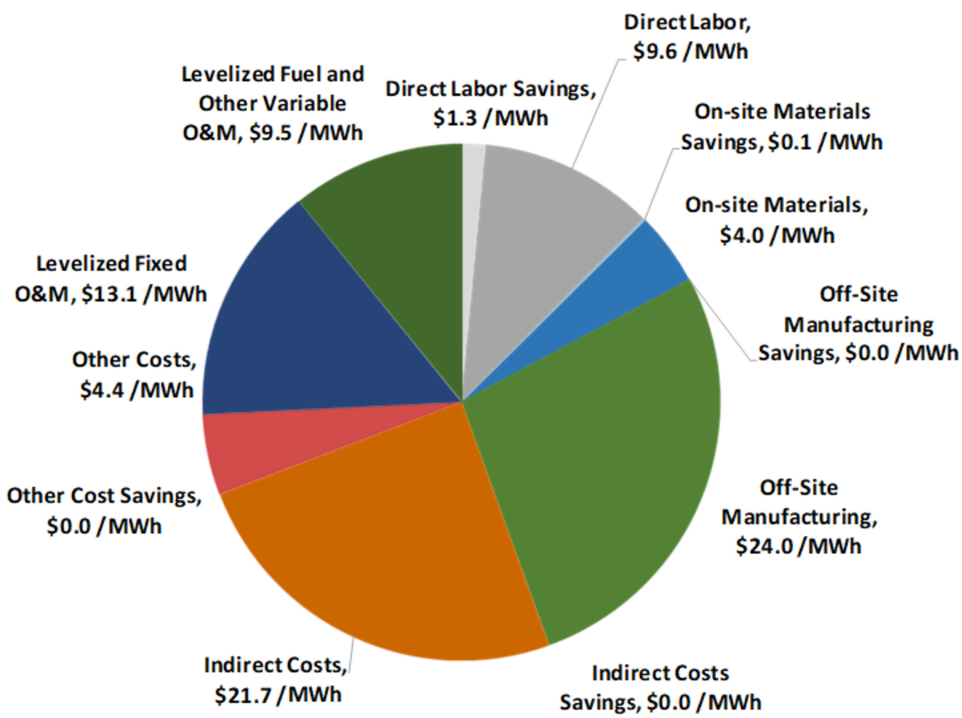

Figure 7-10
LCOE Savings from Example Technology 2 (Construction Method – Labor Reduction)

7.3.3 Tools that Increase Craft Worker Productivity

There are many technologies and practices that increase the productivity of workers. Some of these are discussed in Section 7.1.1. Because these technologies reduce labor hours, they may also reduce construction duration, which results in significant saving of indirect costs. Some example technologies include wearable devices, instituting a more rigorous planning process such as Last Planner System (LPS), worker training, planning for time-phased yard usage, and use of BIM. Some of these ideas are listed in Table 7-18.

An example construction method that reduces labor costs could provide 20% savings on labor on all 2X COAs. If successfully implemented this technology could reduce OCC by $196.4/kW and LCOE by $2.2/MWh. The inputs and results of this calculation are provided in Table 7-10, Table 7-11, Figure 7-11, and Figure 7-12.

Table 7-9
OCC Savings from Example Technology 3 (Craft Worker Productivity)

COA	Labor	Materials	Equipment	Labor	Materials	Equipment	Total Savings
Structures and Improvements (21)	-20%	0%	0%	$112.9/kW	$0.0/kW	$0.0/kW	$112.9/kW
Reactor Equipment (22)	-20%	0%	0%	$24.6/kW	$0.0/kW	$0.0/kW	$24.6/kW
Turbine Generator Equipment (23)	-20%	0%	0%	$12.8/kW	$0.0/kW	$0.0/kW	$12.8/kW
Electrical Equipment (24)	-20%	0%	0%	$10.2/kW	$0.0/kW	$0.0/kW	$10.2/kW
Heat Rejection System (25)	-20%	0%	0%	$15.4/kW	$0.0/kW	$0.0/kW	$15.4/kW
Miscellaneous Equipment (26)	-20%	0%	0%	$20.5/kW	$0.0/kW	$0.0/kW	$20.5/kW
Indirect Costs (3X)	0%			$0.0/kW			$0.0/kW
Total Savings for Example Technology 2 (Construction Methods - Labor)							**$196.4/kW**

Table 7-10
LCOE Savings from Example Technology 3 (Craft Worker Productivity)

COA	Labor	Materials	Equipment	Labor	Materials	Equipment	Total Savings
Structures and Improvements (21)	-25.0%	0.0%	0.0%	$1.3/MWh	$0.0/MWh	$0.0/MWh	$1.3/MWh
Reactor Equipment (22)	-25.0%	0.0%	0.0%	$0.3/MWh	$0.0/MWh	$0.0/MWh	$0.3/MWh
Turbine Generator Equipment (23)	-25.0%	0.0%	0.0%	$0.1/MWh	$0.0/MWh	$0.0/MWh	$0.1/MWh
Electrical Equipment (24)	-25.0%	0.0%	0.0%	$0.1/MWh	$0.0/MWh	$0.0/MWh	$0.1/MWh
Heat Rejection System (25)	-25.0%	0.0%	0.0%	$0.2/MWh	$0.0/MWh	$0.0/MWh	$0.2/MWh
Miscellaneous Equipment (26)	-25.0%	0.0%	0.0%	$0.2/MWh	$0.0/MWh	$0.0/MWh	$0.2/MWh
Indirect Costs (3X)	0%			$0.0%/MWh			0.0/MWh
Total Savings for Example Technology 3 (Craft Worker Productivity)							**$2.2/MWh**

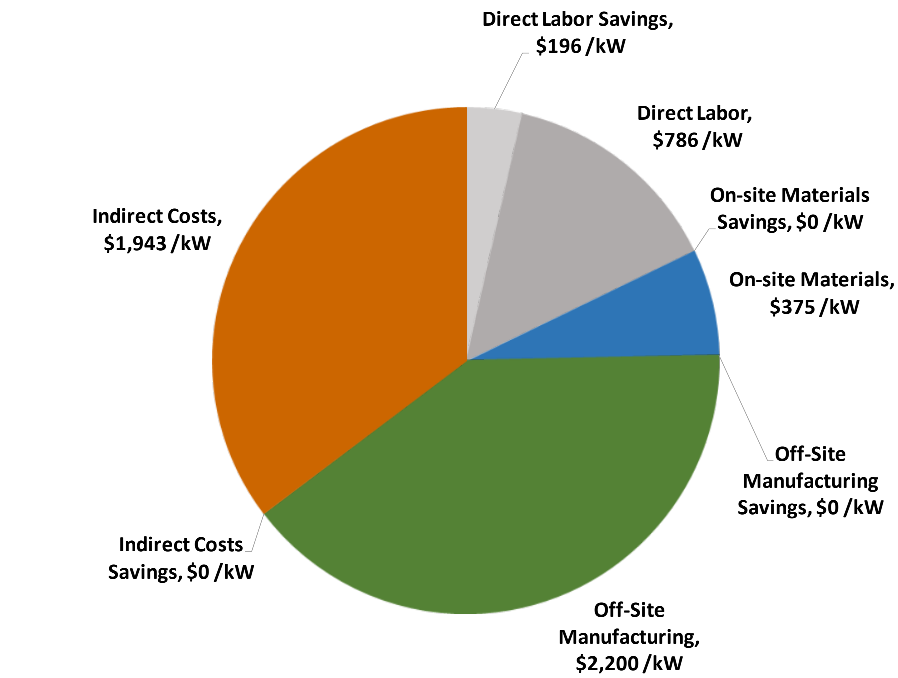

Figure 7-11
OCC Savings from Example Technology 3 (Craft Worker Productivity)

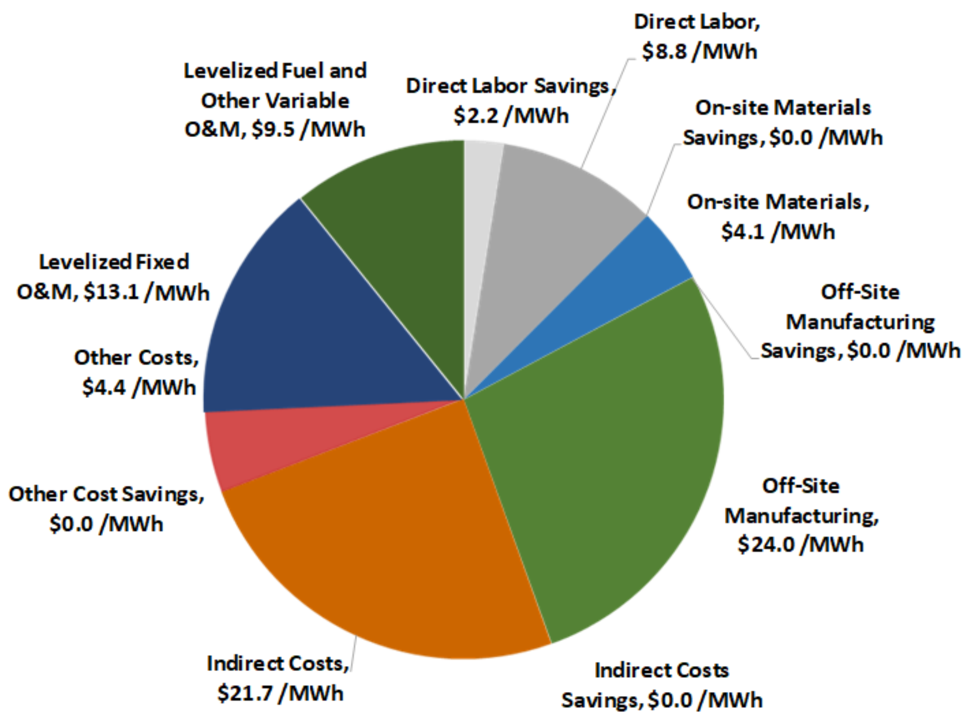

Figure 7-12
LCOE Savings from Example Technology 3 (Craft Worker Productivity)

7.3.4 Methods and Tools that Reduce Construction Duration or Indirect Cost Burden

Sections 7.3.2 and 7.3.3 discuss techniques, tools, and methods that primarily result in decreased craft labor costs. These costs fall under the "direct costs" category. However, much of the labor on site is considered an "indirect cost". The code of accounts under indirect costs are: Field indirect costs (31), Construction supervision (32), Commissioning and startup costs (33), Demonstration test run (34), Design services offsite (35), Project/construction management services offsite (37) and onsite (39), and Design services onsite (38). Some example technologies/methods/tools in this area are remote employee monitoring, design completion prior to starting construction, use of planning software, and 100% design completion. Some of these ideas are listed in Table 7-18.

An example method that could reduce construction duration, could allow some construction activities to be completed in parallel. Table 7-12 and Table 7-13 show the cost savings from an example technology that is assumed to not influence labor, materials, and equipment, but reduce construction duration by 20%. It is observed that labor, materials, and equipment in the LCOE calculation are reduced even though they were unaffected in the calculation of OCC. This is due to the reduction in schedule and the corresponding reduction in interest owed on those components. If successfully implemented, this technology would not impact OCC direct costs, but would reduce OCC (via indirect costs) by 7.9% ($153.7/kW) and LCOE by $4.4/MWh. Note that some of the COAs in Table 7-12 had savings below $0.05/MWh which round to the displayed values of $0.0/MWh. In some cases, the cumulative savings from these categories caused the reported Total Savings (final column) to be greater than the displayed sum of the preceding columns. Figure 7-13 and Figure 7-14 summarize the results of the calculations.

Table 7-11
OCC Savings from Example Technology 4 (Reduction in Construction Time)

COA	Labor	Materials	Equipment	Labor	Materials	Equipment	Total Savings
Structures and Improvements (21)	0%	0%	0%	$0.0/kW	$0.0/kW	$0.0/kW	$0.0/kW
Reactor Equipment (22)	0%	0%	0%	$0.0/kW	$0.0/kW	$0.0/kW	$0.0/kW
Turbine Generator Equipment (23)	0%	0%	0%	$0.0/kW	$0.0/kW	$0.0/kW	$0.0/kW
Electrical Equipment (24)	0%	0%	0%	$0.0/kW	$0.0/kW	$0.0/kW	$0.0/kW
Heat Rejection System (25)	0%	0%	0%	$0.0/kW	$0.0/kW	$0.0/kW	$0.0/kW
Miscellaneous Equipment (26)	0%	0%	0%	$0.0/kW	$0.0/kW	$0.0/kW	$0.0/kW
Indirect Costs (3X)	-8%			$153.7/kW			$153.7/kW
Total Savings for Example Technology 4 (Reduction in Construction Time)							**$153.7/kW**

Table 7-12
LCOE Savings from Example Technology 4 (Reduction in Construction Time)

COA	Labor	Materials	Equipment	Labor	Materials	Equipment	Total Savings
Structures and Improvements (21)	-6.5%	-7.2%	-6.5%	$0.41/MWh	$0.14/MWh	$0.47/MWh	$1.02/MWh
Reactor Equipment (22)	-3.5%	-4.1%	-4.1%	$0.04/MWh	$0.01/MWh	$0.30/MWh	$0.35/MWh
Turbine Generator Equipment (23)	-4.5%	-6.2%	-5.3%	$0.03/MWh	$0.01/MWh	$0.17/MWh	$0.21/MWh
Electrical Equipment (24)	-1.4%	-1.4%	-1.4%	$0.01/MWh	$0.01/MWh	$0.03/MWh	$0.04/MWh
Heat Rejection System (25)	-3.1%	-3.1%	-3.1%	$0.02/MWh	$0.00/MWh	$0.03/MWh	$0.06/MWh
Miscellaneous Equipment (26)	-2.4%	-1.4%	-2.6%	$0.02/MWh	$0.01/MWh	$0.06/MWh	$0.10/MWh
Indirect Costs (3X)	-12%			$2.7/MWh			$2.7/MWh
Total Savings for Example Technology 4 (Reduction in Construction Time)							**$4.4/MWh**

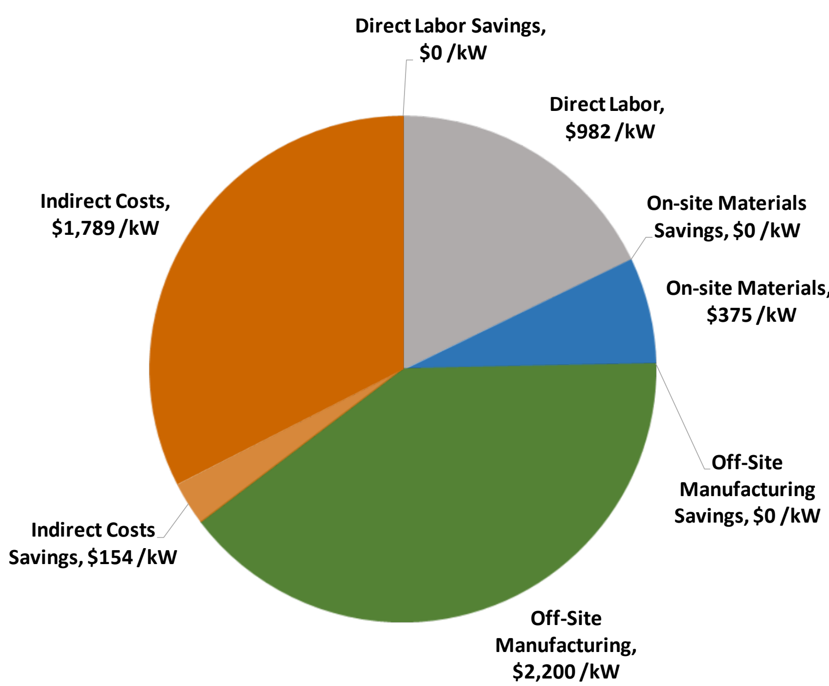

Figure 7-13
OCC Savings from Example Technology 4 (Reduction in Construction Time)

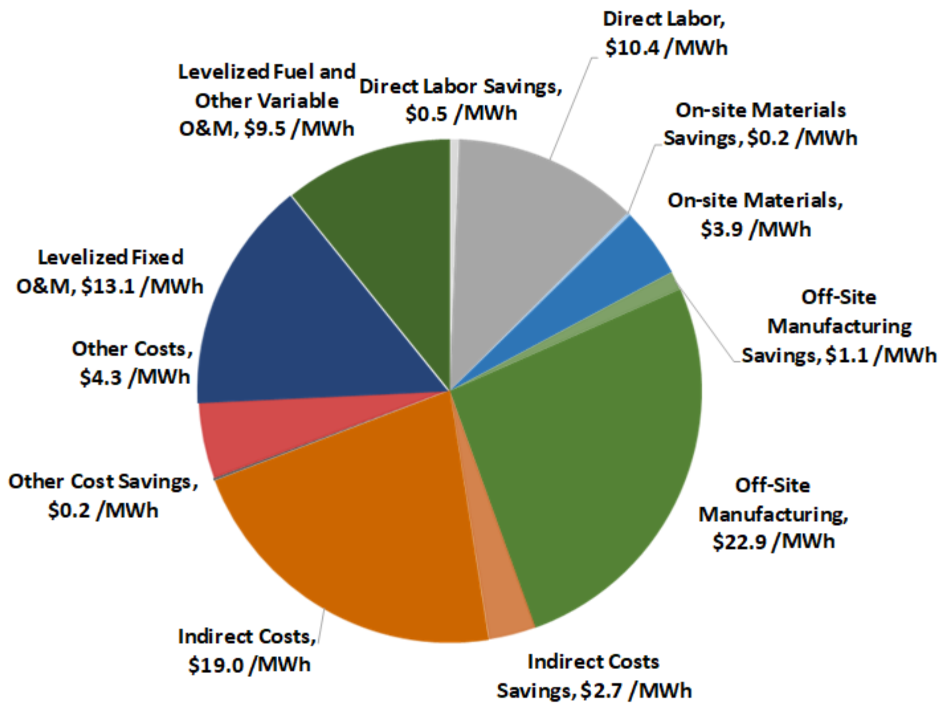

Figure 7-14
LCOE Savings from Example Technology 4 (Reduction in Construction Time)

7.3.5 Improved Manufacturing Techniques for Off-Site Components

As shown in Figure 7-2 off-site manufacturing costs are a greater share of OCC than on-site labor, on-site materials, and indirect costs. If the commercial nuclear industry begins to grow, market forces may drive down the cost of components (and materials) brought to site. Other cost reductions in this area may be the result of the work done in the industry, such as optimization of commercial dedication processes, improving the supply chain (Section 7.1.10), or demonstrations that show the validity of novel techniques to vendors. Some of these ideas are listed in Table 7-18.

An example technology (for example, a supply chain improvement or procurement method) that allows purchasing of off-site equipment needed for structures and improvements (COA 21) at a cost reduction of 20% is considered in this example. Table 7-14 and Table 7-15 show that if successfully implemented this method reduce OCC by $130.0/kW and LCOE by $1.5/MWh. Figure 7-15 and Figure 7-16 summarize the results of these example calculations

Table 7-13
OCC Savings from Example Technology 5 (Reduced Off-Site Manufacturing Costs)

COA	Labor	Materials	Equipment	Labor	Materials	Equipment	Total Savings
Structures and Improvements (21)	0%	0%	-20%	$0.0/kW	$0.0/kW	$130.0/kW	$130.0/kW
Indirect Costs (3X)	0%			$0.0			$0.0/kW
Total Savings for Example Technology 5 (Reduced Off-Site Manufacturing Costs)							**$130.0/kW**

Table 7-14
LCOE Savings from Example Technology 5 (Reduced Off-Site Manufacturing Costs)

COA	Labor	Materials	Equipment	Labor	Materials	Equipment	Total Savings
Structures and Improvements (21)	0.0%	0%	-25%	$0.0/MWh	$0.0/MWh	$1.5/MWh	$1.5/MWh
Indirect Costs (3X)	0%			$0.0/MWh			$0.0/MWh
Total Savings for Example Technology 5 (Reduced Off-Site Manufacturing Costs)							**$1.5/MWh**

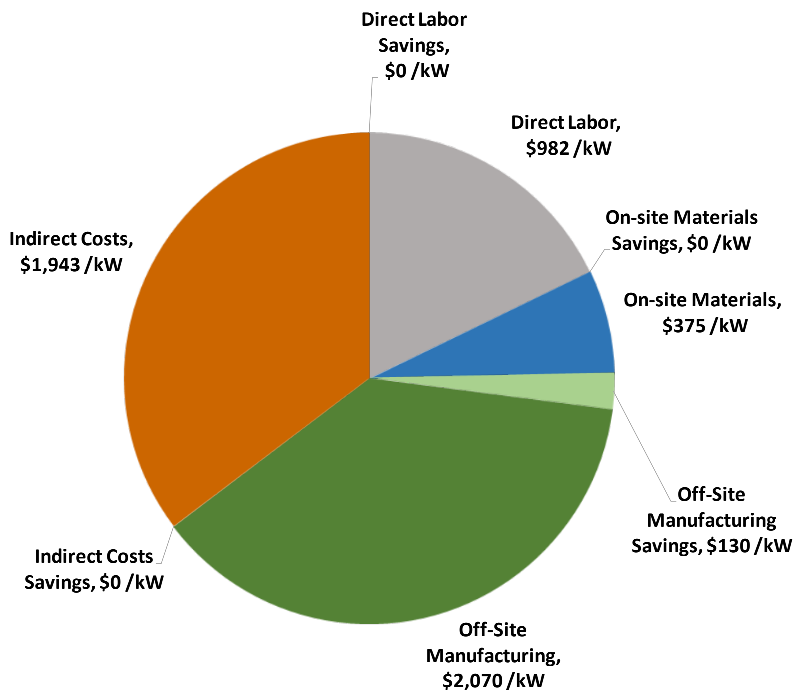

Figure 7-15
OCC Savings from Example Technology 5 (Reduced Off-Site Manufacturing Costs)

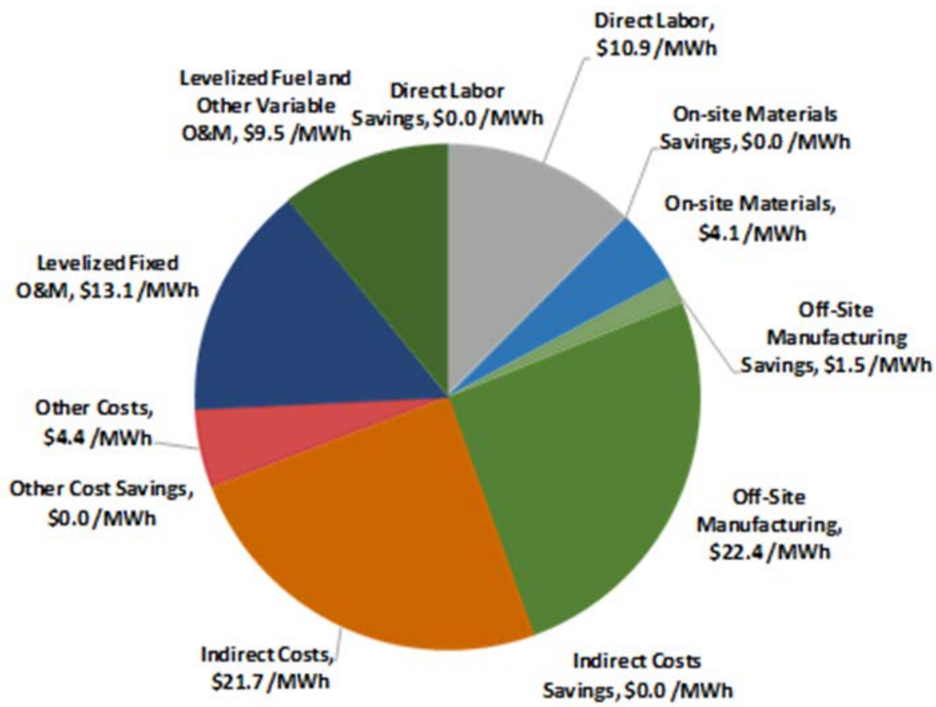

Figure 7-16
LCOE Savings from Example Technology 5 (Reduced Off-Site Manufacturing Costs)

7.3.6 Design for Economic Construction

As discussed in Section 7.1.3, there are design changes that can be made to reduce the construction costs. This can come by planning to make structures easier to build, components easier to install, redesigning systems so the new systems are fundamentally cheaper, or by redesigning the plant such that whole systems are non-existent. Savings in this category may change each cost category in different ways with a net cost reduction. Some examples include designing the plant such that some systems or components are no longer needed, designing such that safety related components are no longer safety related, increased use of modularity, use of seismic isolation, use of ATF, and replacing the linear no-dose threshold. Some of these ideas are listed in Table 7-18.

These kinds of projects redesign components/structures and therefore affect all aspects of those components/structures. An example project could reduce the cost of labor by 10%, materials by 10%, equipment by 5%, and duration by 15% for COA 21. Table 7-16, Table 7-17, show that if successfully implemented, it could reduce OCC by $146.2/kW and LCOE by $2.2/MWh. Figure 7-17, and Figure 7-18 summarize the results of these example calculations

Table 7-15
OCC Savings from Example Technology 6 (Example Component Redesign)

COA	Labor	Materials	Equipment	Labor	Materials	Equipment	Total Savings
Structures and Improvements (21)	-10%	-10%	-5%	$56.5/kW	$17.0/kW	$32.5/kW	$106.0/kW
Indirect Costs (3X)	-2%			$40.2/kW			$40.2/kW
Total Savings for Example Technology 6 (Example Component Redesign)							**$146.2/kW**

Table 7-16
LCOE Savings from Example Technology 6 (Example Component Redesign)

COA	Labor	Materials	Equipment	Labor	Materials	Equipment	Total Savings
Structures and Improvements (21)	-12.5%	-13.1%	-6.6%	$0.7/MWh	$0.2/MWh	$0.5/MWh	$1.5/MWh
Indirect Costs (3X)	-3%			$0.7/MWh			$0.7/MWh
Total Savings for Example Technology 6 (Example Component Redesign)							**$2.2/MWh**

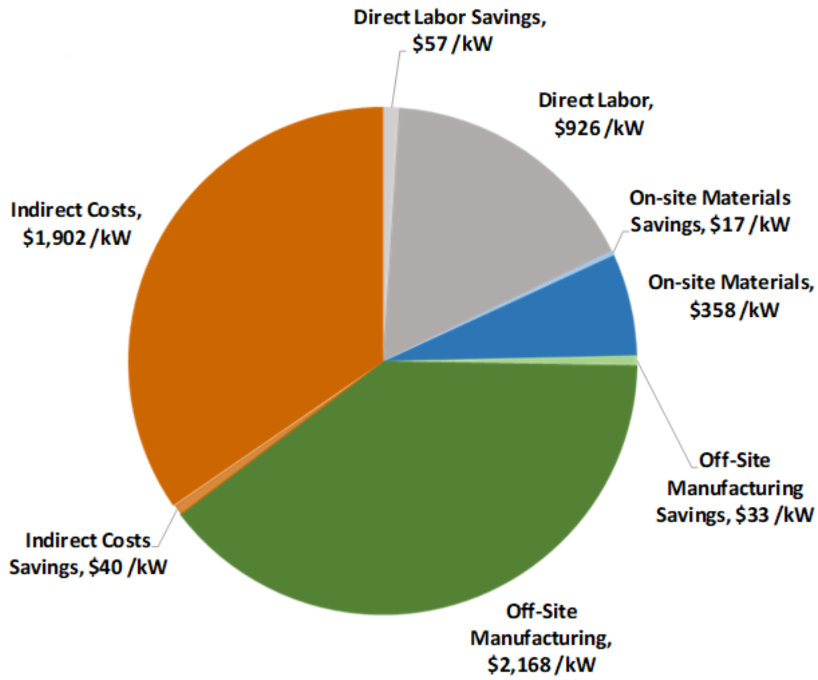

Figure 7-17
OCC Savings from Example Technology 6 (Example Component Redesign)

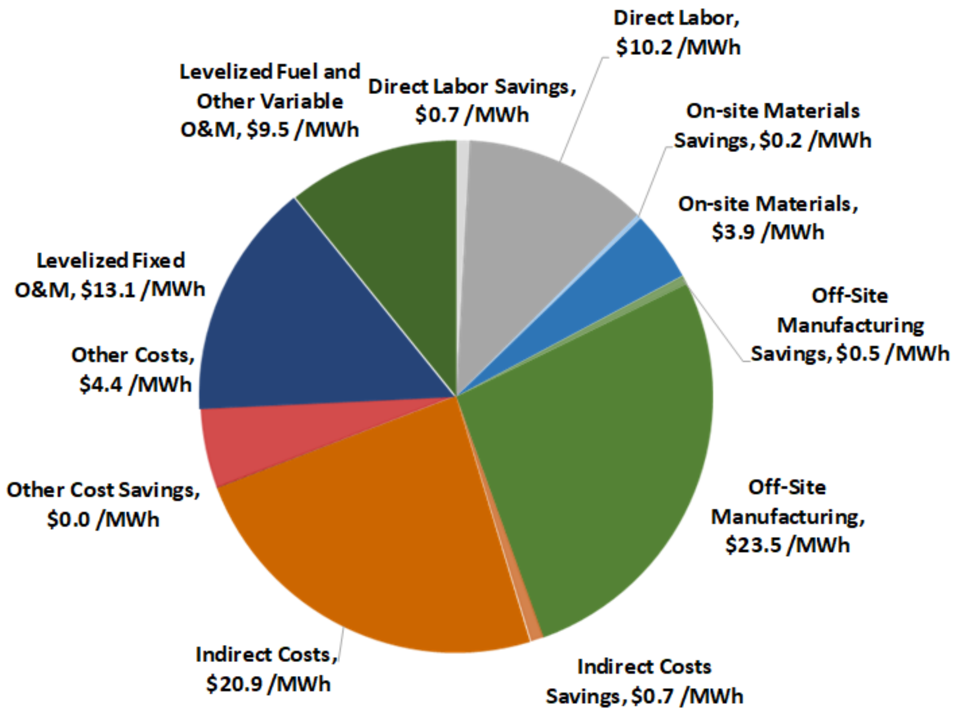

Figure 7-18
LCOE Savings from Example Technology 6 (Example Component Redesign)

7.3.7 Summary List

The previous Sections 7.3.1 through 7.3.6 described six generic example technologies that could reduce the baselines cost in different ways. The amount of decreased costs for each example technology is highly dependent on how many COAs were affected, and on the multiplier chosen to reduce each cost. In general, technology areas are likely to have a large impact if they meet some or all of the following criteria:

- Decrease interference between resources: Many of the solutions that address worker productivity focus on eliminating competition between resources. Huge savings can be found if more activities are allowed to run in parallel.
- Reduce project timeline: Timeline reductions reduce the amount of interest that must be paid during construction.
- Affect multiple cost drivers: Technologies that span multiple cost drivers are more likely to have a significant impact on cost.
- Affect multiple components: Technologies that span multiple components provide more opportunities for cost savings.

Table 7-18 provides a summary of 57 technologies that could be used to reduce the cost drivers identified in Section 7.1. Also, the EPRI ANT focus area that each of the specified technology most closely aligns with, was identified.

Many technologies were also identified as technologies that other programs (e.g., DOE, GAIN, University, Code Committees, National Labs, etc.) would also be well suited to investigate. A lettered system was used to determine the market focus (Generation III/III+, SMRs, or advanced reactors) and the expected cost impact on direct costs, indirect costs, interest during construction, operating and maintenance costs, and fuel costs. The letters used were L for impacts estimated to be less than \$50/kWe (<1% of OCC), M for \$50-200/kWe (1-5% of OCC), and H for >200/kWe (>5%).

The time period on which the technology was expected be able to be deployed is also listed (0-5 years, 5-10 years, 10-20 years). Specific ways in which each technology impacts OCC or LCOE are also identified. Note that these estimates are somewhat qualitative because the level of detail for each technology needed to accurately assess expected benefits is not universally available.

Table 7-17
Evaluation of R&D Opportunities

Area	R&D Opportunity	No.	Specific Examples	Impact Summary (See Report Section 7): *Advanced Materials*	*Construction Methods*	*Worker Productivity*	*Construction Duration*	*Improved Techniques for Off-site Components*	*Design for Economic Construction*	EPRI: AMM	ECI	C&IO	Other EPRI	Other Programs: DOE, GAIN, University, Code Committees, Natl Labs, etc.	Market Focus: Gen III and GenIII+ LWR	SMR LWR	Advanced Reactors	Time Horizon: Available Today	0-5 years	5-10 years	10-20 yrs. +	Enabling Technology (e.g. for advanced Reactors)	Expectations Regarding Cost Impact (Judgement Based) – Construction: *Directs*	*Indirects*	Overall Reduction in OCC	Commercial Operations: *IDC*	*O&M*	*Fuel*	Overall Reduction LCOE
Advanced Manufacturing and Materials	Advanced Materials	1	New Materials for Advanced Reactors (e.g., HT, creep resist, MS compatible, env. deg. resistance)	Note 1									•	•	L	M	H			•		•	Note 1						
		2	Extended Codification of Existing Materials (e.g. 617)											•	L	L			•	Ongoing		•							
		3	Composites as Structural Members or Components	•						•				•	M	M	M	•	Ongoing				L		L				
		4	High Strength ODS Materials											•	L	M	H	Some	•	Ongoing		•							
		5	High Yield Strength Rebar for Nuclear	•		•			•	•					H	H	H		•	Ongoing			L		L				
		6	Additive Manufacturing - Special Components (e.g. valves, fuel components)	•					•	•				•	L	H	H		•	Ongoing			L						
		7	Additive and advanced manufacturing- major components (RPVH)	•					•	•				•	L	H	H			•			L	L	L		L		L
		8	HDPE Piping Applications	•					•				•		M	M	M	•	Ongoing				L		L		L		L
		9	Residual stress mitigation (RSM)	•	•				•				•	•	H	H	DD	•	Ongoing								L		L
		10	New inhibitors and coatings	•					•				•		M	M	M	•	Ongoing								L		L
		11	Self consolidating concrete	•	•		•		•				•	•	H	H	H		•	Ongoing			L	L	L				
	Advanced Joining	12	Improved conventional welding technologies		•				•	•				•	L	H	H	•	Ongoing				L	L	L				
		13	New advanced welding (e.g., E-beam)		•		•			•				•	L	H	H			•			L		L		L		L
		14	Mechanical Splicing Technologies for Rebar		•	•	•		•					•	M	M	DD			•			L		L				
		15	M&S of Materials Fabrication and Joining		•				•				•	•	L	M	M	•	Ongoing				L		L				
	Structures	16	Novel external event shielding											•	M	M	DD			•		•							

Note 1: Enabling Technologies "Required" or Prerequisites and as Such are Not Modeled

Note 2: L = <$50/kWe on OCC; M= $50-200/kWe (1-5%); H= >200/kWe (>5%); DD= Design Dependent

Table 7-17
Evaluation of R&D Opportunities (continued)

Area	R&D Opportunity	No.	Examples of Specific Impacts (Economic and Other)																										Amenable to Quantitative Modeling for R&D Roadmap		
			Plant Construction and Commissioning													Plant Commercial Mission and Operations												D&D			
			Reduced Costs of Comps, Materials or Commodities	Reduced Cost of PM and Oversight (indirects)	Reduced Construction or Fabrication Time	Reduced Labor Costs	Supports Higher Worker Productivity	Higher Quality (reduced rework)	Consistent with "Standardization"	Supports "Completed Design" Concept	Improved/Streamlined NDE during Construction	Enhances Project Management Efficiency	Supports/Facilitates Commissioning and ITAAC	Supports Fabricability and Constructability Objectives	Other	Improved/Enhanced Tech, Design or Functionality	Improved Plant Capacity or Availability	New Plant Capability or Feature	Improved Human Performance	Improved Operations	Improved Reliability	Enhanced Plant Performance	Reduced Maintenance	Reduce ISI Scope and Demands (time)	Enhanced Safety	Supports Alternate Mission (e.g., Process	Other	Facilitates D&D	OCC	LCOE	Plant reliability, component integrity, security, etc.
Advanced Manufacturing and Materials	Advanced Materials	1												•		•		•							•	•			Note 1		
		2												•		•		•							•	•					
		3	•		•			•	•		•			•		•					•	•	•	•				•	•	•	
		4														•		•							•	•					
		5	•	•	•	•	•	•	•		•			•		•								•					•	•	
		6	•			•		•	•		•			•				•											•	•	
		7	•		•	•		•	•		•			•		•							•	•					•	•	
		8	•			•			•					•		•					•	•	•	•	•			•	•	•	
		9							•							•	•				•	•	•	•	•	•					•
		10							•							•	•		•		•	•	•	•	•	•		•	•	•	•
		11			•	•	•		•		•																		•	•	
	Advanced Joining	12	•	•	•	•	•	•						•							•			•					•	•	•
		13	•	•	•	•	•	•			•			•		•					•			•					•	•	•
		14	•	•	•	•	•							•															•	•	
		15			•	•	•	•	•		•			•							•		•	•					•	•	•
	Structures	16														•		•						•	•	•					

Note 1: Enabling Technologies "Required" or Prerequisites and as Such are Not Modeled

Note 2: L = <$50/kWe on OCC; M= $50-200/kWe (1-5%); H= >200/kWe (>5%); DD= Design Dependent

Table 7-17
Evaluation of R&D Opportunities (continued)

Area	R&D Opportunity	No.	Specific Examples	Impact Summary (See Report Section 7)						EPRI				Other Programs	Market Focus			Time Horizon					Expectations Regarding Cost Impact (Judgement Based): Construction			Expectations Regarding Cost Impact (Judgement Based): Commercial Operations			
				Advanced Materials	*Construction Methods*	*Worker Productivity*	*Construction Duration*	*Improved Techniques for Off-site Components*	*Design for Economic Construction*	AMM	ECI	C&ID	Other EPRI	DOE, GAIN, University, Code Committees, Natl Labs, etc.	Gen III and GenIII+ LWR	SMR LWR	Advanced Reactors	Available Today	0-5 years	5-10 years	10-20 yrs. +	Enabling Technology (e.g. for advanced Reactors)	*Directs*	*Indirects*	**Overall Reduction in OCC**	*IDC*	*O&M*	*Fuel*	**Overall Reduction LCOE**
Advanced Construction Practices, Methods and Technologies	Practices	17	Conventional (e.g., Gen III /III+) nuclear modularization		•			•	•		•			•	M	M	M	•	Ongoing				M	M	M				
		18	Super modules		•		•		•		•			•	H	M	DD	•	Ongoing				M	M	M				
		19	Smart Batch Plant fopr Concrete		•		•	•							H	M	DD		•	Ongoing			L		L				
		20	Factory fabrication and assembly		•		•	•	•		•			•	M	M	M	•	Ongoing				L	L	L				
		21	Open Top Construction		•		•		•		•				H	DD	DD	•					L	L	L				
		22	Floor by floor construction and commissioning		•	•	•		•		•				H	DD	DD	•					L	L	L				
	Methods	23	Alternative and advanced concrete formwork		•	•	•		•		•			•	M	M	DD		•	Ongoing			L	L	L				
		24	Moisture tolerant coatings for construction support (facilitates open top)		•	•	•		•		•			•	M	DD	DD	•					L	L	L				
	Technologies	25	Methods for improved concrete inspection during construction (e.g., embedded sensors)			•	•		•		•			•	M	M	M		•	Ongoing			L	L	L				
		26	Automated inspection of components and structures			•	•		•		•			•	H	H	H		•	Ongoing			L	L	L	L	L		
		27	Machine learning (general)			•	•		•					•	TBD	TBD	TBD			•									
		28	Advanced NDE for concrete (GPR)			•	•		•				•	•	H	M	DD		•	Ongoing			L	L	L				
		29	Surface mounted seismic sensors			•	•		•						TBD	TBD	TBD										L		
		30	Robotics/drones			•	•		•				•	•	M	M	M	•	Ongoing				L	L	L				
Worker Productivity Tools	Tools	31	Wearable devices			•	•		•				•	•	H	H	H	•	Ongoing				L	L	L				
		32	Worker tracking monitoring			•	•	•	•					•	TBD	TBD	TBD												
		33	Planning tools and technologies (e.g., Last Planner System®)			•	•	•	•					•	H	H	H	•	Ongoing				L	L	L				
	Practices	34	SOTA training tools			•	•	•	•				•	•	H	H	H	•	Ongoing										
		35	Process Hazard Analysis (PHA-PRA)				•	•	•		•			•	TBD	H	H	•	Ongoing								M		M

Note 1: Enabling Technologies "Required" or Prerequisites and as Such are Not Modeled

Note 2: L = <$50/kWe on OCC M= $50-200/kWe (1-5%) H= >200/kWe (>5%) DD= Design Dependent

Table 7-17
Evaluation of R&D Opportunities (continued)

Area	R&D Opportunity	No.	Examples of Specific Impacts (Economic and Other)																										Amenable to Quantitative Modeling for R&D Roadmap		
			Plant Construction and Commissioning											Plant Commercial Mission and Operations												D&D			
			Reduced Costs of Comps, Materials or Commodities	Reduced Cost of PM and Oversight (indirects)	Reduced Construction or Fabrication Time	Reduced Labor Costs	Supports Higher Worker Productivity	Higher Quality (reduced rework)	Consistent with "Standardization"	Supports "Completed Design" Concept	Improved/Streamlined NDE during Construction	Enhances Project Management Efficiency	Supports/Facilitates Commissioning and ITAAC	Supports Fabricability and Constructability Objectives	Other	Improved/Enhanced Tech, Design or Functionality	Improved Plant Capacity or Availability	New Plant Capability or Feature	Improved Human Performance	Improved Operations	Improved Reliability	Enhanced Plant Performance	Reduced Maintenance	Reduce ISI Scope and Demands (time)	Enhanced Safety	Supports Alternate Mission (e.g., Process	Other	Facilitates D&D	OCC	LCOE	Plant reliability, component integrity, security, etc.
Advanced Construction Practices, Methods and Technologies	Practices	17	•	•	•	•		•	•	•	•	•	•	•							•	•	•	•					•	•	
		18	•	•	•	•		•	•	•	•	•	•	•							•	•	•	•					•	•	
		19	•	•	•	•		•						•															•	•	
		20	•	•	•	•		•	•	•	•	•	•	•							•	•	•	•					•	•	
		21			•	•	•		•					•															•	•	
		22			•	•	•		•				•	•															•	•	
	Methods	23	•		•	•	•							•															•	•	
		24	•		•	•	•							•															•	•	
	Technologies	25			•	•	•	•			•			•															•	•	
		26			•	•		•			•																		•	•	•
		27		•	•	•	•	•	•		•	•	•	•			•		•	•	•	•	•	•	•				•	•	•
		28			•	•	•	•			•			•															•	•	•
		29																						•	•				•	•	•
		30			•	•	•	•													•		•	•					•	•	•
Worker Productivity Tools	Tools	31		•	•	•	•	•				•	•						•	•	•	•			•			•	•	•	
		32		•	•	•	•	•				•	•															•	•	•	
		33	•	•	•	•	•	•																				•	•	•	
	Practices	34		•	•	•	•	•				•	•						•	•	•				•			•	•	•	•
		35																	•	•	•		•	•	•			•			•

Note 1: Enabling Technologies "Required" or Prerequisites and as Such are Not Modeled

Note 2: L = <$50/kWe on OCC M= $50-200/kWe (1-5%) H= >200/kWe (>5%) DD= Design Dependent

Table 7-17
Evaluation of R&D Opportunities (continued)

Area	R&D Opportunity	No.	Specific Examples	Impact Summary (See Report Section 7): Advanced Materials	Construction Methods	Worker Productivity	Construction Duration	Improved Techniques for Off-site Components	Design for Economic Construction	EPRI: AMM	ECI	C&IO	Other EPRI	Other Programs: DOE, GAIN, University, Code Committees, Nat'l Labs, etc.	Market Focus: Gen III and GenIII+ LWR	SMR LWR	Advanced Reactors	Time Horizon: Available Today	0-5 years	5-10 years	10-20 yrs. +	Enabling Technology (e.g. for advanced Reactors)	Expectations Regarding Cost Impact (Judgement Based) – Construction: Directs	Indirects	Overall Reduction in OCC	Commercial Operations: IDC	O&M	Fuel	Overall Reduction LCOE
Project Enabling Tools and Technologies	Tools	36	Augmented Reality			•	•		•				•	•	H	H	H	•		Ongoing			L	L	L				
		37	Artificial Intelligence			•	•		•				•	•	H	H	H	•		Ongoing			L	L	L				
		38	4D Simulations			•	•	•	•					•	H	H	H	•		Ongoing			L	L	L				
		39	Build Information Management (BIM Tools)			•	•	•	•					•	H	H	H	•		Ongoing			L	L	L				
		40	Risk Informed Inspection			•	•	•	•				•	•	M	H	H		•	Ongoing							M		M
		41	Risk Informed Licensing						•				•		H	H	H							M	M		M		M
		42	SOTA planning and scheduling platform, software and supporting technologies			•	•	•	•					•	H	H	H	•		Ongoing			H	H	H				
Industry Infrastructure of for Materials, Commodities and Supplies	Practices	43	Increased use of CDG				•		•				•		H	H	H	•		Ongoing			M		M				
		44	Industry audit and training technologies and tools				•		•				•	•	H	H	H		•	Ongoing			L		L				
	Technologies to support Supply Chain	45	Training technologies (AR, offline learning)						•				•	•	H	H	H		•	Ongoing			L		L				
		46	Improved guidelines for vendors						•						H	H	H		•	Ongoing			L		L				
Commissioning and Operations (C&IO)	Tools	47	PREDIX® type technologies for commissioning and ITAAC support						•					•	L	H	H		•	Ongoing				L	L				
		48	Digital twins, predictive monitoring for commissioning						•					•	L	H	H		•	Ongoing			L	L	L		M		M
		49	Data Management and Analytics						•					•	L	H	H		•	Ongoing			L	L	L		M		M
Other Opportunities (not included in this study)	Technologies	50	ATF						•																			•	
		51	Seismic Isolation						•														•	•		•	•		
		52	Digital I&C						•														•				•		
		53	Cyber Security/Encryption						•																		•		
	Siting	54	Source term, LNT and EPZ effects						•														•	•			•		
	Programmatic	55	Facilitates Realization of NOAK Economies of Scale																										
		56	Enables Positive Learning Curves																										
		57	Improved methods, practices and timelines of adopting consensus codes and standards			•			•														•	•			•		

Note 1: Enabling Technologies "Required" or Prerequisites and as Such are Not Modeled

Note 2: L = <$50/kWe on OCC; M= $50-200/kWe (1-5%); H= >200/kWe (>5%); DD= Design Dependent

Table 7-17
Evaluation of R&D Opportunities (continued)

Area	R&D Opportunity	No.	Examples of Specific Impacts (Economic and Other)																										Amenable to Quantitative Modeling for R&D Roadmap		
			Plant Construction and Commissioning													Plant Commercial Mission and Operations												D&D			
			Reduced Costs of Comps, Materials or Commodities	Reduced Cost of PM and Oversight (indirects)	Reduced Construction or Fabrication Time	Reduced Labor Costs	Supports Higher Worker Productivity	Higher Quality (reduced rework)	Consistent with "Standardization"	Supports "Completed Design" Concept	Improved/Streamlined NDE during Construction	Enhances Project Management Efficiency	Supports/Facilitates Commissioning and ITAAC	Supports Fabricability and Constructability Objectives	Other	Improved/Enhanced Tech, Design or Functionality	Improved Plant Capacity or Availability	New Plant Capability or Feature	Improved Human Performance	Improved Operations	Improved Reliability	Enhanced Plant Performance	Reduced Maintenance	Reduce ISI Scope and Demands (time)	Enhanced Safety	Supports Alternate Mission (e.g., Process	Other	Facilitates D&D	OCC	LCOE	Plant reliability, component integrity, security, etc.
Project Enabling Tools and Technologies	Tools	36		•	•	•	•	•				•	•	•					•	•			•		•			•	•	•	•
		37		•	•	•	•	•				•	•	•					•	•			•		•			•	•	•	•
		38			•		•	•				•	•																•	•	
		39	•	•	•	•	•	•	•			•	•																•	•	
		40																		•	•		•	•	•						•
		41			•															•	•		•	•	•				•	•	•
		42	•	•	•	•	•	•			•	•	•															•	•	•	
Industry Infrastructure of for Materials, Commodities and Supplies	Practices	43	•		•																								•	•	•
		44	•		•																								•	•	
	Technologies to support Supply Chain	45	•	•	•																								•	•	
		46	•	•	•																								•	•	
Commissioning and Operations (C&IO)	Tools	47			•						•		•	•															•	•	
		48			•						•		•	•					•	•	•	•	•	•	•				•	•	
		49			•						•		•	•					•	•	•	•	•	•	•				•	•	
Other Opportunities (not included in this study)	Technologies	50																													
		51																													
		52																													
		53																													
	Siting	54																													
	Programmatic	55																													
		56																													
		57																													

Note 1: Enabling Technologies "Required" or Prerequisites and as Such are Not Modeled

Note 2: L = <$50/kWe on OCC M= $50-200/kWe (1-5%) H= >200/kWe (>5%) DD= Design Dependent

8
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A

EPRI/GAIN/NEI WORKSHOP MATERIALS

ELECTRIC POWER RESEARCH INSTITUTE

EPRI / GAIN / NEI

WORKSHOP ABOUT ECONOMICS-BASED R&D FOR NUCLEAR POWER CONSTRUCTION

January 17–18, 2019 • Washington, DC

TOGETHER...SHAPING THE FUTURE OF ELECTRICITY

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AGENDA

EPRI / GAIN / NEI's
Workshop about Economics-Based R&D for Nuclear Power Construction

January 17-18, 2019
Nuclear Energy Institute / 1201 F Street NW, Suite 100 / Washington, DC 20004

OBJECTIVE: present the latest economic-related research on the costs associated with constructing nuclear power plants; and, to spur discussion and solicit input about EPRI's current project titled, *Economic Based R&D Roadmap for New Nuclear Power*

THURSDAY, JANUARY 17, 2019		
TIME	**TOPIC**	**PRESENTER**
8:00 a.m.	Registration and Breakfast	
8:30 a.m.	**1. Welcome and Introduction** Review of ANT Program; Workshop overview and purpose	David B. Scott, EPRI
9:00 a.m.	**2. Economic Perspective – US** New reactor cost reduction	Marc Nichol, NEI
9:30 a.m.	**3. MIT Study on Nuclear Power Cost** The future of nuclear energy in a carbon-constrained world	Eric Ingersoll, Lucid Catalyst
10:00 a.m.	Break	
10:30 a.m.	**4. Economic Perspective – UK** ETI Nuclear cost drivers project	Eric Ingersoll, Lucid Catalyst
11:00 a.m.	**5. Analysis of US Historical Capital Costs** The historical construction cost and cost drivers of nuclear power plants	Francesco Ganda, Argonne National Laboratory
11:30 a.m.	**6. Economic drivers, barriers, and impacts in the United States** Exploring the role of advanced nuclear in future energy markets	Andrew Sowder, EPRI
12:00 p.m.	Lunch	
1:00 p.m.	**7. Economic Based R&D Roadmap** Current findings from EPRI's R&D roadmap development	Chuck Marks, Dominion Engineering
2:00 p.m.	**8. Open Discussion – Cost Driver Category #1** Participant input on current findings from the R&D roadmap development	Led by EPRI / Dominion Engineering (attendee participation)
2:30 p.m.	**9. Open Discussion – Cost Driver Category #2** Participant input on current findings from the R&D roadmap development	Led by EPRI / Dominion Engineering (attendee participation)
3:00 p.m.	Break	
3:30 p.m.	**10. Open Discussion – Cost Driver Category #3** Participant input on current findings from the R&D roadmap development	Led by EPRI / Dominion Engineering (attendee participation)
4:00 p.m.	**11. Open Discussion – Cost Driver Category #4** Participant input on current findings from the R&D roadmap development	Led by EPRI / Dominion Engineering (attendee participation)
4:30 p.m.	Adjourn	

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AGENDA

EPRI / GAIN / NEI's
Workshop about Economics-Based R&D for Nuclear Power Construction

January 17-18, 2019
Nuclear Energy Institute / 1201 F Street NW, Suite 100 / Washington, DC 20004

FRIDAY, JANUARY 18, 2019		
TIME	**TOPIC**	**PRESENTER / LEAD**
8:00 a.m.	Breakfast	
8:25 a.m.	**12. Recap**	David B. Scott, EPRI
8:30 a.m.	**13. Open Discussion – Cost Driver Category #5** Participant input on current findings from the R&D roadmap development	Led by EPRI / Dominion Engineering (attendee participation)
9:00 a.m.	**14. Open Discussion – Cost Driver Category #6** Participant input on current findings from the R&D roadmap development	Led by EPRI / Dominion Engineering (attendee participation)
9:30 a.m.	**15. Roadmap Development for R&D** Participant input on R&D multiyear plan	Led by EPRI / Dominion Engineering (attendee participation)
10:00 a.m.	Break	
10:30 a.m.	**16. Roadmap Development for R&D (continued)** Participant input on R&D multiyear plan	Led by EPRI / Dominion Engineering (attendee participation)
11:30 a.m.	**17. Advanced Reactor (AR) Construction** Application of R&D roadmap and additional AR needs	Led by EPRI / Dominion Engineering (attendee participation)
12:00 p.m.	Lunch and Adjourn	

Together . . . Shaping the Future of Electricity

January 19, 2019

Workshop Highlights

Advanced Nuclear Technology (ANT) Program
EPRI-GAIN-NEI Workshop About Economics-Based R&D for Nuclear Power Construction
Date: January 17-18, 2019
Location: Nuclear Energy Institute / 1201 F Street NW, Suite 1100 / Washington, DC 20004

Introduction

At the referenced date, a workshop was held at the Nuclear Energy Institute (NEI) and co-hosted by EPRI, GAIN, and NEI. The impetus for the workshop was an existing study being performed by EPRI's Advanced Nuclear Technology (ANT) group to identify cost estimating methods used by the nuclear power industry, develop a tool for analyzing construction costs, and develop a roadmap to direct future research and development towards reducing construction costs of nuclear power plants. The name of the ANT project is, *Economics-Based R&D for New Nuclear Plant Development*. It is being co-funded by ClearPath, EPRI, GAIN, NEI, and NuScale. The workshop provided the opportunity to relay the current results of the ANT study and receive industry input on the accuracy of identified cost drivers for nuclear power plant construction and potential technological solutions. More specifically and as stated in the invitation for the event, the goal was to

- *Learn about the recent international studies on cost drivers.*
- *Hear about the specific results coming from EPRI's cost study on construction.*
- *Engage in open discussion about technologies that can reduce construction costs.*

On November 19, 2018, workshop invitations were distributed to various industry stakeholders. Registration and attendance was high. The following provides a summary of the Workshop.

Workshop Structure

The first half-day of the work consisted of presentations made by representatives of various historical and current studies on nuclear power construction economics. The seven presentations at the beginning of the workshop was intended to provide the referential datum by which the open discussion portion of the workshop was to be conducted. The open discussion lasted for the balance of the workshop and included dialogue about the previously identified cost drivers for nuclear power plants and potential solutions for those cost drivers. The following consists of summaries of the presentations and open discussion.

<u>ANT Program and Workshop Overview (David B. Scott, EPRI)</u>

EPRI provided an overview of the ANT program and projects directed towards addressing cost reductions for constructing commercial nuclear power plants. The presentation and ensuing discussion covered:

- The mission of EPRI, Nuclear sector, and ANT
- ANT's technical focus areas and the specific research focus areas related to engineering, procurement, and construction research
- ANT research activities to address constructability and structural design, seismic isolation, reinforced concrete, advanced manufacturing, and factory fabrication

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January 19, 2019

- ANT research activities to address construction economics
- Workshop objective and structure

NEI Perspective (Marc Nichol, NEI)

NEI provided an overall summary of their perspective on U.S. economics related to new construction of nuclear power plants. The presentation included a summary of the following.

- Nuclear generation in the United States for the operating fleet and new construction
- Policy and economic drivers for new plant construction
- Construction comparisons between natural gas CC and nuclear power plants
- NEI strategy to propel nuclear market share

The Future of Nuclear Energy in a Carbon-Constrained World (Eric Ingersoll, Lucid Catalyst on behalf of the study performed by MIT-Interdisciplinary group)

On behalf of the MIT-Interdisciplinary team, Eric Ingersoll gave a summary of the recently released MIT study which included the following topics.

- The role new nuclear power could play in decarbonizing the power sector and its comparative role against competitive energy resources
- Cost breakdowns of nuclear power plant designs based on historical studies and one-on-one communications
- Summary of potential technologies to reduce nuclear power construction costs
- The role of advanced reactor designs in cost reduction
- The role of polity in the future growth or attrition of nuclear power construction

Nuclear Cost Drivers Project (Eric Ingersoll, Energy Lucid Catalyst on behalf of the study performed by Energy Technologies Institute)

On behalf of the MIT-Interdisciplinary team, Eric Ingersoll gave a summary of the recently released MIT study which included the following topics.

- Cost breakdowns of an average nuclear power plant
- The identified cost drivers: design, materials, equipment, construction implementation, labor, governance, regulation, supply chain, and operations
- Scoring methods for aligning cost results based on benchmarks and global regions
- Global case studies that included comparison with off-shore wind

Analysis of United States Historical Capital Costs (Francesco Ganda, Argonne National Laboratory)

Previous studies performed by Francesco Ganda provided increased details about the historical construction costs and drivers for commercialized nuclear power plants. More specifically, the following was discussed during the presentation.

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January 19, 2019

- A comparison of overnight construction costs, construction durations, and cost overruns for US nuclear power plants
- Specific cost drivers: design changes during construction, contractual frameworks, and regulatory framework
- Cost escalations per discipline / material / SSC
- A comparison of the effect of cost drivers and design changes

Economic Drivers, Barriers, and Impacts in the United States and the Role of Advanced Nuclear in Future Energy Markets (Andrew Sowder, EPRI)

EPRI provided a summary of the role that advanced reactor designs can play in the US energy markets. The topics included the following.

- Capital cost trajectories of varied energy resources and the competitiveness of nuclear
- Estimations of energy supply and demand based on the EPRI-owned economic model – REGEN-**R**egional **E**conomy, **G**HG, and **En**ergy
- The role of economic conditions and energy policy towards the potential growth of nuclear power construction - price of natural gas, production tax credits, carbon tax, increased revenue options, regional factors

Economic Based R&D Roadmap (Chuck Marks, Dominion Engineering on behalf of the ANT Group)

As the Principal Investigator of the EPRI/ANT Economic Roadmap study, Dominion Engineering provided the to-date results of the project. The slides and presentation was the dominant reference for the continued open-discussion segment of the workshop. More specifically, it included the following.

- The purpose and scope of the ANT project on economics-based R&D
- The methods of evaluating construction costs and the results of studying previous construction cost estimations
- Historical and contemporary cost drivers according to a standardized code of accounts
- Cost driver delineation into six (6) categories – directs costs, indirect costs, project preparation, project implementation and execution, technical issues, and realization of advanced technologies and practices.
- Potential technology opportunities for the cost drivers (e.g., modularization, advanced concrete, seismic isolation, advanced manufacturing, robotics)

Open Discussion (Open to all attendees and participants)

The final scope of the workshop was to provide a forum for open discussion on the topic of the specific drivers of constructing nuclear power plants. The conversation did periodically include non-technical issues such as regulatory input and contractual practices. However, the non-technical discussions did lead to potential technical solutions for these non-technical issues; and, the open discussion included an abundant amount of discussions on innovative technologies that address new construction costs for large light-water reactors, small modular reactors, and advanced (Generation IV) reactor designs. Please see the following slides title, *Workshop about Economics-Based R&D for Nuclear Power Construction /*

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Open Discussion and Ideation, in this package for further details.

Attendees

The workshop was well attended with industry representatives from utilities, research institutes, national laboratories, subject matter experts, and academia. The following table indicates those who signed-in at the workshop or announced their attendance by phone.

Name	Company
Irfan Ali	Advanced Reactor Concepts (ARC)
Francesco Ganda	Argonne National Laboratory
Hussein Khalil	Argonne National Laboratory
Marsha Bala	Battelle Energy Alliance, LLC
Rita Baranwal	Battelle Energy Alliance, LLC
Lori Braase	Battelle Energy Alliance, LLC
Mark Dehart	Battelle Energy Alliance, LLC
Efe Kurt	Battelle Energy Alliance, LLC
Muhammad Fahmy	Bechtel Power Corporation
Ahmet Tokpinar	Bechtel Power Corporation
Arantxa Cuadra	Brookhaven National Laboratory
Terry Garrett	Burns & McDonnell Engineering Co.
Joe Chaisson	Clean Air Task Force
Armond Cohen	Clean Air Task Force
Brett Rampal	Clean Air Task Force
Spencer Nelson	ClearPath Foundation, Inc.
Calvin McCall	Concrete Engineering Consultants, Inc.
Chuck Marks	Dominion Engineering, Inc.
Jeff Reinders	Dominion Engineering, Inc.
Bob Varrin	Dominion Engineering, Inc.
David Julius	Duke Energy Corp.
Neil Kern	Duke Energy Corp.
David Scott	Electric Power Research Institute (EPRI)
Andrew Sowder	Electric Power Research Institute (EPRI)
Vincent Maupu	Electricite de France S.A.
Amaury Coullet	Embassy of France
Greg Gibson	Excel Services
Farshid Shahrokhi	Framatome, U.S. Operations
David Hinds	GE Hitachi Nuclear Energy Americas, LLC
Michael Ford	Harvard University
Tatsu Sakamoto	Hitachi-GE Nuclear Energy, Ltd.
Yuriko Suzuki	Hitachi-GE Nuclear Energy, Ltd.
Sonny Kim	Joint Global Change Research Institute
Eric Ingersoll	LucidCatalyst
Koroush Shirvan	Massachusetts Institute of Technology

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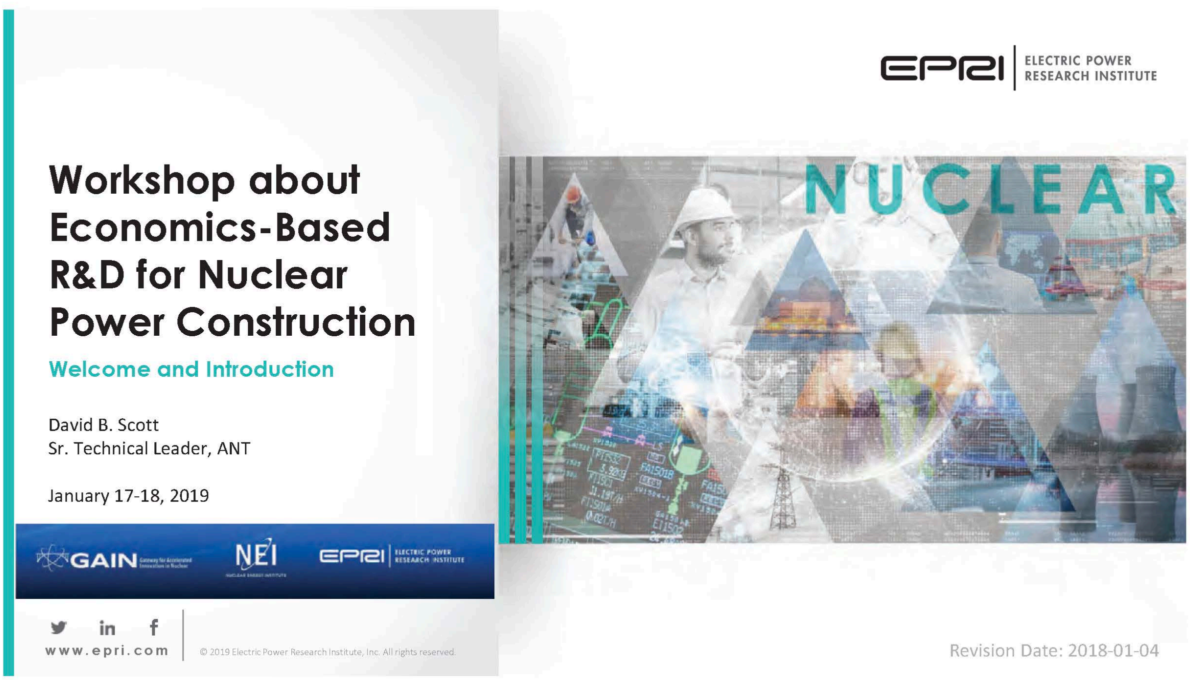
Doug Chapin	MPR Associates, Inc.
Kati Austgen	Nuclear Energy Institute
Harsh S. Desai	Nuclear Energy Institute
Marcus Nichol	Nuclear Energy Institute
Everett Redmond	Nuclear Energy Institute
Ashley Finan	Nuclear Innovation Alliance (NIA)
Mike Brasel	NuScale Power, LLC
Andrew Worrall	Oak Ridge National Laboratory
Christopher Deir	Ontario Power Generation, Inc.
Lubna Ladak	Ontario Power Generation, Inc.
Lauren Lathem	Southern Company Services, Inc.
Jason Redd	Southern Nuclear Operating Co.
Art Wharton	Studsvik
TJ Butcher	Teledyne Brown Engineering, Inc.
Spencer Klein	Tennessee Valley Authority (TVA)
Tara Neider	TerraPower
Canon Bryan	Terrestrial Energy, Inc.
Bret Kugelmass	Titans of Nuclear / Energy Impact Center
Alice Caponiti	U.S. Dept. of Energy
Andrew Whittaker	University at Buffalo
Gil Brown	University of Massachusetts Lowell
Lou Qualls	UT Battelle, LLC
Gavin Ridley	Yellowstone Energy
Sam Shaner	Yellowstone Energy

Workshop About Economics-Based R&D for Nuclear Power Construction
January 17 and 18, 2019
Nuclear Energy Institute
Washington, DC
Please join us to gather stakeholder input about technologies to reduce construction costs of commercial nuclear power plants.
GAIN Gateway for Accelerated Innovation in Nuclear
NEI
EPRI ELECTRIC POWER RESEARCH INSTITUTE
Registration and information: www.epri.com



Workshop about Economics-Based R&D for Nuclear Power Construction
Welcome and Introduction
David B. Scott
Sr. Technical Leader, ANT
January 17-18, 2019
GAIN
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NUCLEAR
Revision Date: 2018-01-04

Content

- Overview – EPRI/Nuclear/ Advanced Nuclear Technology (ANT)
- Select ANT Projects Related to NPP Construction Cost
- Workshop Objectives and Design

EPRI's Mission

Advancing ***safe***, ***reliable***, ***affordable,*** and ***environmentally responsible*** electricity for society through global collaboration, thought leadership and science & technology innovation


EPRI Nuclear R&D: Global Collaboration and Reach
GLOBAL PARTICIPANTS
GLOBAL BREADTH & DEPTH
>320 reactors worldwide
>75% of the world's commercial nuclear units
Participants Encompass Most Nuclear Reactor Designs
5
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ANT Program Mission
The EPRI Advanced Nuclear Technology (ANT) Program leads Research and Development (R&D) through EPRI's collaborative model to proactively evaluate and address issues regarding the near-term deployment of advanced nuclear plant designs.
MISSION
Basic Research and Development
National Laboratories, Universities
Collaborative Technology Development, Integration and Application
EPRI
Technology Commercialization
Suppliers, Vendors
The ANT Program is a scientific research program for those around the world and at various stages of new nuclear plant development and deployment, concentrating on the economic, technical, and regulatory issues that could affect the ability to license, construct, start-up, and operate new nuclear reactors.
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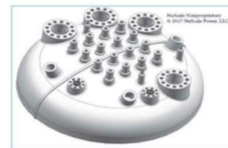
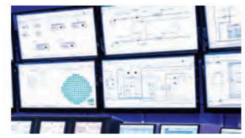
ANT Technical Focus Areas

- **Engineering, Procurement, and Construction**
  - Siting, design, construction materials, and construction activities of the plant, including modular construction



- **Materials and Components**
  - Class 1, 2, and 3 piping systems and related components such as valves, heat exchangers, and pumps
  - Optimize methods for fabrication, installation, joining, inspection, and operations, including chemistry
  - New applications of materials and components



- **Modern Technology Application**
  - Maximize the use of existing, new, and (possibly) non-nuclear-specific technology in new nuclear plants
  - Gaps for the use of digital systems in new nuclear applications

- **Advance Reactor TI Program**
  - Strategic analysis and economics, technology assessment and tool development (ex. PHA-PRA), materials, owner-operator requirements

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Engineering, Procurement, and Construction – Construction

- **Constructability**
  - Provide guidance to designers and structural engineers on designing to ease construction, focusing on labor, schedule, and possible re-work reductions, in lieu of material efficiency
  - Identification of potential systems and structures of where this approach may be most applicable

- **Projects**
  - Guide to Designing Structures for Constructability (sch. 2019)
  - Performance-Based Design for Civil and Structural Applications (sch. 2020-2021)

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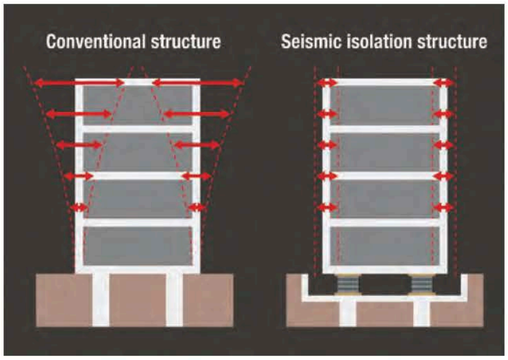
Engineering, Procurement, and Construction – Seismic

- **Seismic Isolation**
  - Structural member sizes and equipment anchorage are affected by seismic demand
  - System, structure, and component robustness, qualification, and cost are affected by seismic demand
  - Seismic isolation cost-benefit is unknown at sites
  - Parametric study showing if there is financial benefit of seismic isolation
- **Projects**
  - Seismic Isolation of Nuclear Power Plants (2013)
  - Cost Basis for Utilizing Seismic Isolation for Design (sch. 2019)



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Engineering, Procurement, and Construction – Reinforcement

- **Reinforcing Steel**
  - Temporally expensive
  - Higher Yield Strength → 100-120 ksi (690-830 MPa)
  - Reduce volume, construction time, material cost, congestion (voids)
  - Generating data needed to modify ACI 349 and 359 to allow credit for high-strength reinforcing (100 and 120 ksi [690 and 830 MPa]) in safety-related structures
- **Projects**
  - High-Strength Reinforcing Steel (2015, 2016, 2017)
  - Investigating Mechanical Splicing of Reinforcing Steel (2017)
  - Field Guide for Inspections of Reinforced Concrete Construction (sch. 2019)
  - Automated QA Inspection for Reinforcing Steel (sch. 2020-2021)
  - Alternative Concrete Reinforcement Materials (sch. 2020-2021)
  - Automated Rebar Tying for Nuclear New Builds (sch. 2021-2022)

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Engineering, Procurement, and Construction – Concrete

- **Concrete-Related Research**
  - Temporally expensive
  - Structurally relevant to meet the demands of pressure, dead weight, seismic requirements, and impact
  - Concrete mixtures can be difficult to manage and sensitive to process variation; and defects sometimes develop
- **Projects**
  - Conducting Quality Inspections and Tests of Concrete Placement at Nuclear Facilities (2013)
  - Demonstration and Evaluation of Self-Consolidating Concrete (SCC) Mixtures (2016)
  - Mass Concrete Modeling and Temperature Control (2018)
  - Optimization of Concrete Placements (2018)
  - Demonstration of SCC Flow Simulation Software (sch. 2019)
  - Best Practices for SCC as Mass Concrete (sch. 2019-2021)

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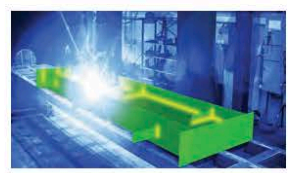
Engineering, Procurement, and Construction – Structural Steel

- **Advanced Structural Welding**
  - Fabrication of steel modules for S-C construction is laborious and slow
  - The use of advanced welding techniques (electron beam welding, friction-stir, etc.) has been shown to dramatically increase welding speed in laboratory environments
  - Field deployable technique would be useful for civil/structural applications
  - Identify techniques and their potential benefits that are most applicable for civil-related applications
  - Develop for field use
  - Demonstrate application on construction modules and / or other structural steel
  - Adapt field-version for structural steel welds
- **Project**
  - Advanced Welding for Infrastructure and Construction (sch. 2019-2021)



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Materials & Components – Advanced Manufacturing

- **Advanced Manufacturing and Fabrication**
  - Industry needs optimizing the fabrication process of components
- **Projects**
  - Powder Metallurgy–Hot Isostatic Pressing (2017, 2018)
  - Thick Section Welding (2017)
  - Demonstration of Powder Metallurgy - Hot Isostatic Pressing
  - SMR Vessel Advanced Manufacturing Program (sch. 2020)

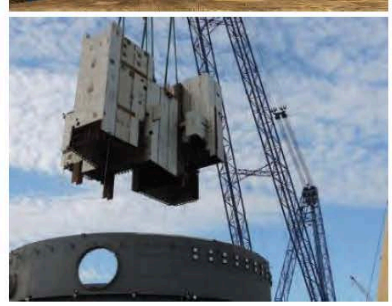
65mm (thick) x 3m length
Welding time: <10 minutes
Photograph provided courtesy: TWI (UK)

40%-scale, upper head using Powder Metallurgy-Hot Isostatic Pressing (PM-HIP)

Representative Model of NuScale Power Reactor Vessel

Materials & Components – Factory Fabrication of Models and Components

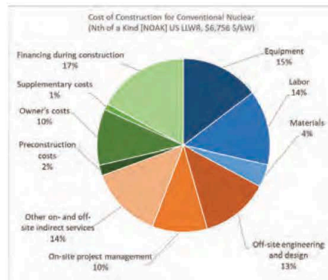
- **Factory Fabrication of Models and Components**
  - A significant portion of construction and fabrication expense (schedule and labor) is from work conducted onsite
  - Manufacturing in a factory environment could lead to lower costs and better construction schedules
  - Scope
    - Gather lessons learned from constructors, fabricators, and utilities involved in the recent construction of commercial nuclear power plants and organizations involved in other modular construction projects
    - Conduct a gap analysis to understand and document the technologies and processes needed to enable more factory fabrication
    - Develop a roadmap to guide future research in closing the gaps of factory fabrication
- **Project**
  - A Pathway to Factory Fabrication for Modules and Components (sch. 2019)



Source: World Nuclear News

Engineering, Procurement, and Construction – Cost Drivers

- **Construction Costs for New Nuclear**
  - Construction cost data has been broad and specifics are unclear
  - Support is needed to develop economics-based cost-benefit methods and evaluation models to help focus EPRI-, government-, and industry-related R&D initiatives toward reducing new plant costs
  - There is need to assess cost-drivers for existing ALWRs, SMRs, and advanced reactors in order to give quantitative evaluation of the cost-benefit of new technologies or processes
  - R&D roadmap development and prioritization can be generated as a result of comparing cost-benefit methods and drivers against the current best available data
- **Project**
  - Economic-Based R&D Roadmap for New Nuclear Plant Development (sch. 2019)



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Economic Based R&D for New Nuclear Plant Development

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NEI NUCLEAR ENERGY INSTITUTE

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Objectives

present the latest economic-related research on the costs associated with constructing nuclear power plants; and, to spur discussion and solicit input about EPRI's current project titled, *Economic Based R&D Roadmap for New Nuclear Power*

Agenda (Morning / Afternoon)

Workshop about Economics-Based R&D for Nuclear Power Construction

Morning Session, January 17, 2019

Time	Topic	Lead
8:00 am	Registration and Breakfast	
8:30 am	**1. Welcome and Introduction** Review of ANT Program; Workshop overview and purpose	D. Scott, EPRI
9:00 am	**2. Economic Perspective – US** New reactor cost reduction	M. Nichol, NEI
9:30 am	**3. MIT Study on Nuclear Power Cost** The future of nuclear energy in a carbon-constrained world	E. Ingersoll, Lucid Catalyst
10:00 am	Break	
10:30 am	**4. Economic Perspective – UK** ETI Nuclear cost drivers project	E. Ingersoll, Lucid Catalyst
11:00 am	**5. Analysis of US Historical Capital Costs** The historical construction cost and cost drivers of nuclear power plants	F. Ganda, Argonne National Laboratories
11:30 am	**6. Economic drivers, barriers, and impacts in the US** Exploring role of advanced nuclear in future energy markets	A. Sowder, EPRI
12:00 pm	Lunch	

Workshop about Economics-Based R&D for Nuclear Power Construction

Afternoon Session, January 17, 2019

Time	Topic	Lead
1:00 pm	**7. Economic Based R&D Roadmap** Current findings from EPRI's R&D roadmap development	C. Marks, DEI
2:00 pm	**8. Open Discussion – Cost Driver Category #1** Participant input on current findings from the R&D roadmap development	Led by EPRI / DEI (attendee participation)
2:30 pm	**9. Open Discussion – Cost Driver Category #2** Participant input on current findings from the R&D roadmap development	Led by EPRI / DEI (attendee participation)
3:00 pm	Break	
3:30 pm	**10. Open Discussion – Cost Driver Category #3** Participant input on current findings from the R&D roadmap development	Led by EPRI / DEI (attendee participation)
4:00 pm	**11. Open Discussion – Cost Driver Category #4** Participant input on current findings from the R&D roadmap development	Led by EPRI / DEI (attendee participation)
4:30 pm	Adjourn	

Agenda (Morning)

Workshop about Economics-Based R&D for Nuclear Power Construction

Morning Session, January 18, 2019

Time	Topic	Lead
8:00 am	Breakfast	
8:25 am	**12. Recap**	D. Scott, EPRI
8:30 am	**13. Open Discussion – Cost Driver Category #5** Participant input on current findings from the R&D roadmap development	Led by EPRI / DEI (attendee participation)
9:00 am	**14. Open Discussion – Cost Driver Category #6** Participant input on current findings from the R&D roadmap development	Led by EPRI / DEI (attendee participation)
9:30 am	**15. Roadmap Development for R&D** Participant input on R&D multiyear plan	Led by EPRI / DEI (attendee participation)
10:00 am	Break	
10:30 am	**16. Roadmap Development for R&D (continued)** Participant input on R&D multiyear plan	Led by EPRI / DEI (attendee participation)
11:30 am	**17. Advanced Reactor (AR) Construction** Application of R&D roadmap and additional AR needs	Led by EPRI / DEI (attendee participation)
12:00 am	Lunch and Adjourn	

Together...Shaping the Future of Electricity

U.S. Economic Perspective

NEI/EPRI/GAIN Economics-Based R&D Workshop

January 17, 2019

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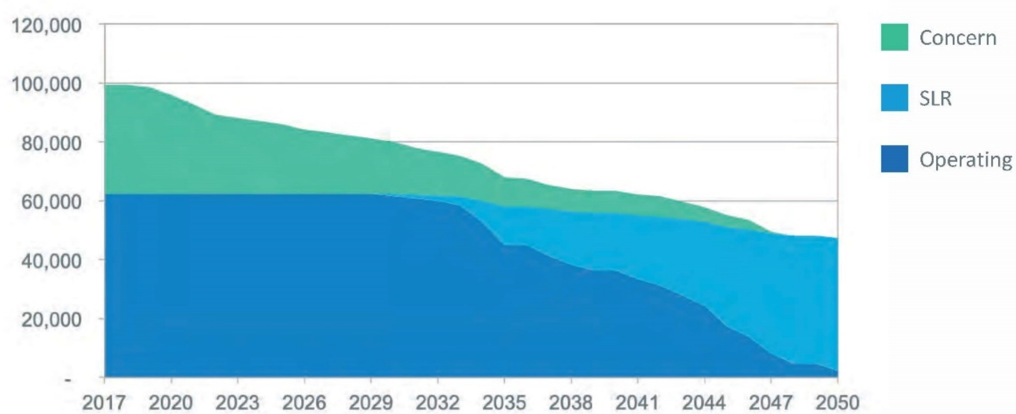
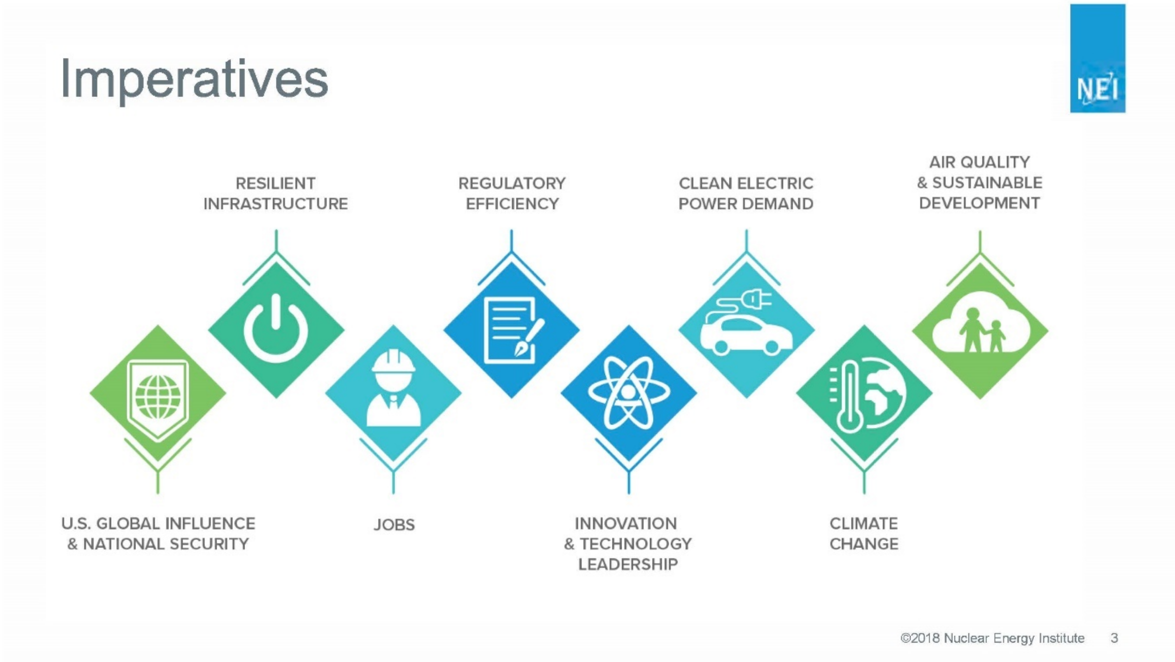
The Challenge

The U.S. could lose half of its nuclear generation by 2050




Imperatives
NEI
RESILIENT INFRASTRUCTURE
REGULATORY EFFICIENCY
CLEAN ELECTRIC POWER DEMAND
AIR QUALITY & SUSTAINABLE DEVELOPMENT
U.S. GLOBAL INFLUENCE & NATIONAL SECURITY
JOBS
INNOVATION & TECHNOLOGY LEADERSHIP
CLIMATE CHANGE
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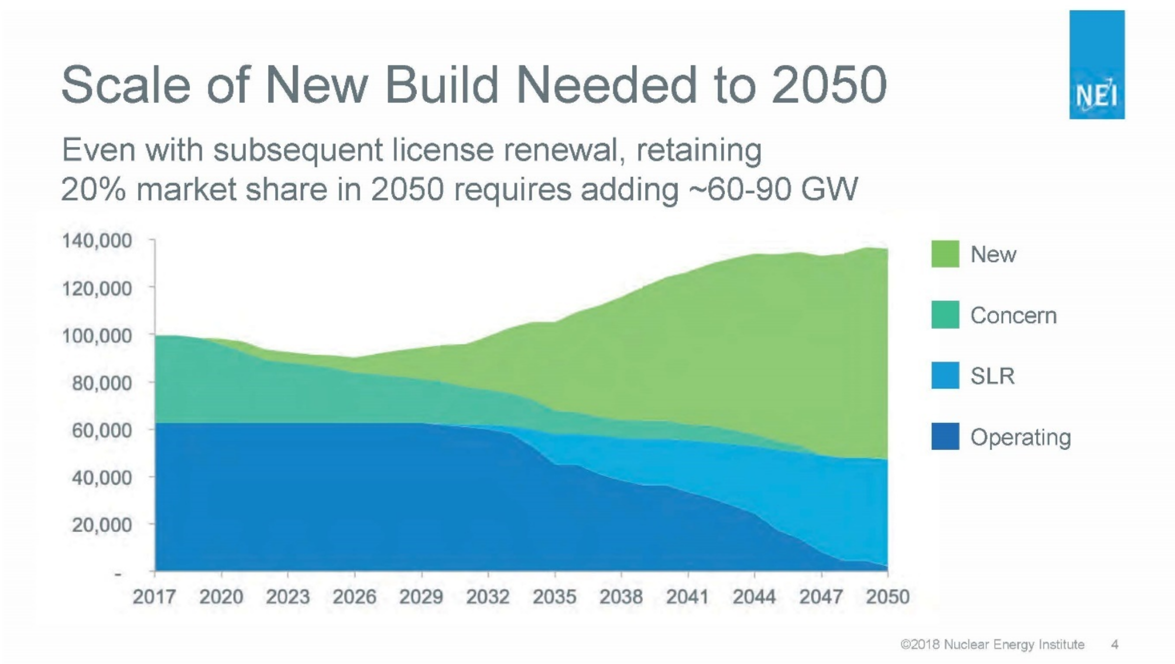
Scale of New Build Needed to 2050
NEI
Even with subsequent license renewal, retaining
20% market share in 2050 requires adding ~60-90 GW
140,000
120,000
100,000
80,000
60,000
40,000
20,000
-
2017 2020 2023 2026 2029 2032 2035 2038 2041 2044 2047 2050
New
Concern
SLR
Operating
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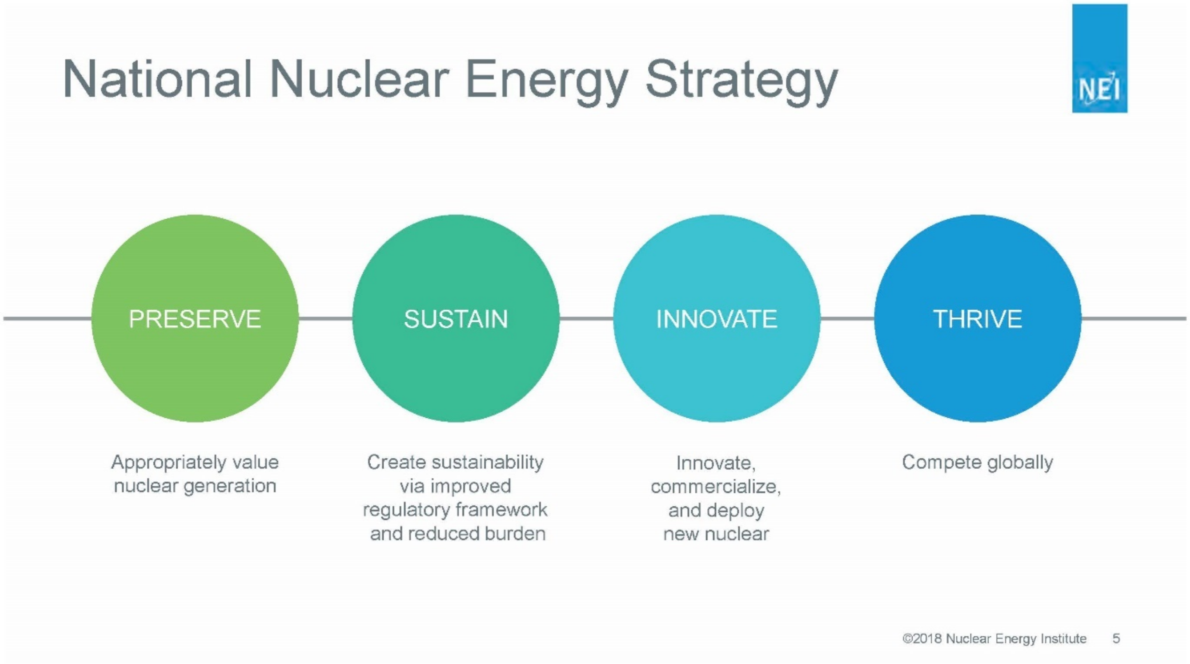
National Nuclear Energy Strategy
NEI
PRESERVE
SUSTAIN
INNOVATE
THRIVE
Appropriately value nuclear generation
Create sustainability via improved regulatory framework and reduced burden
Innovate, commercialize, and deploy new nuclear
Compete globally
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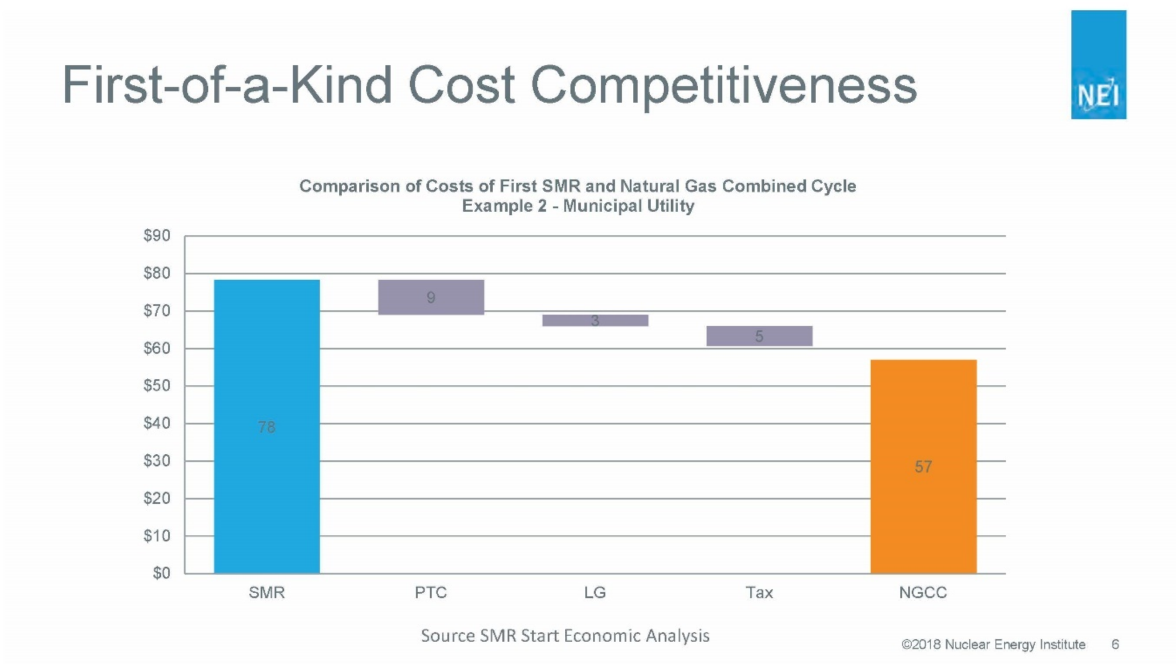
First-of-a-Kind Cost Competitiveness
NEI
Comparison of Costs of First SMR and Natural Gas Combined Cycle
Example 2 - Municipal Utility
$90
$80
$70
$60
$50
$40
$30
$20
$10
$0
78
9
3
5
57
SMR
PTC
LG
Tax
NGCC
Source SMR Start Economic Analysis
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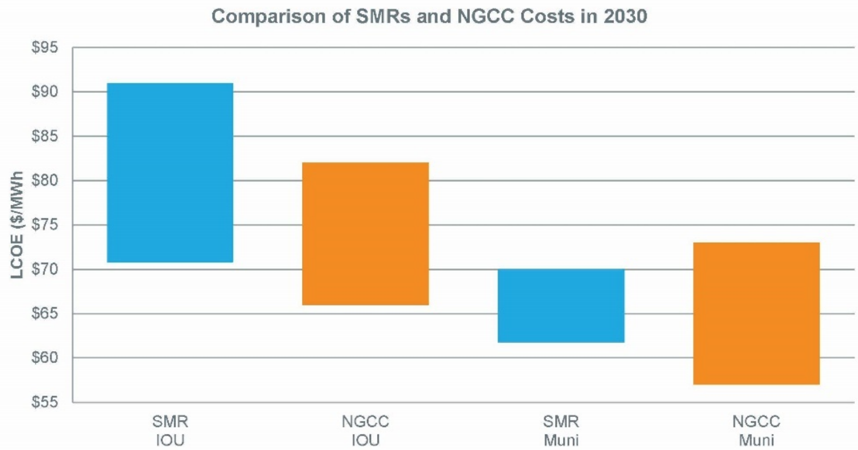
Nth-of-a-Kind Cost Competitiveness

NEI



Source SMR Start Economic Analysis

Path to Cost Competitiveness

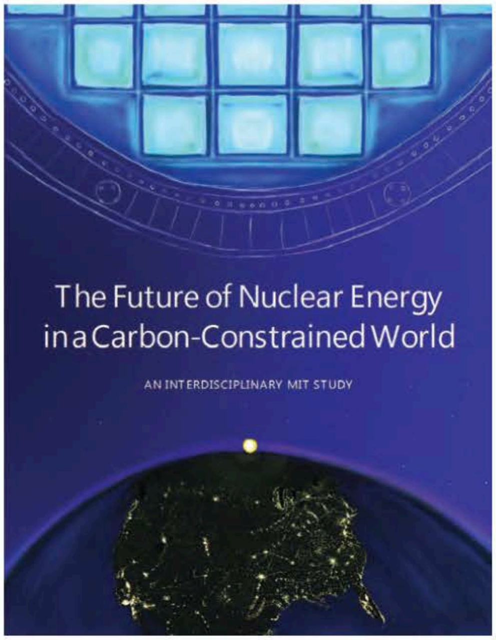
NEI

On-the-grid reactors

- LCOE below $50/kWh, in some markets below $30/kWh
- Construction costs dominate for most reactors
- Target: About half the cost and half the schedule of today's new reactor construction

Other applications

- Off-grid electric: ~$300/kWh
- Non-electric uses (e.g., heat, hydrogen)



David Petti
Executive Director, INL

Jacopo Buongiorno
Co-Director, MIT

Michael Corradini
Co-Director, U-Wisconsin

John Parsons
Co-Director, MIT

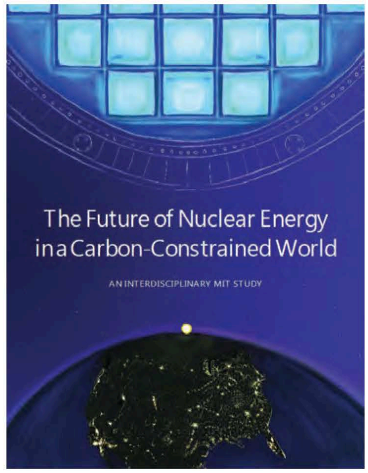
MITei
MIT Energy Initiative

NSE
Nuclear Science and Engineering
science : systems : society

Take-away messages

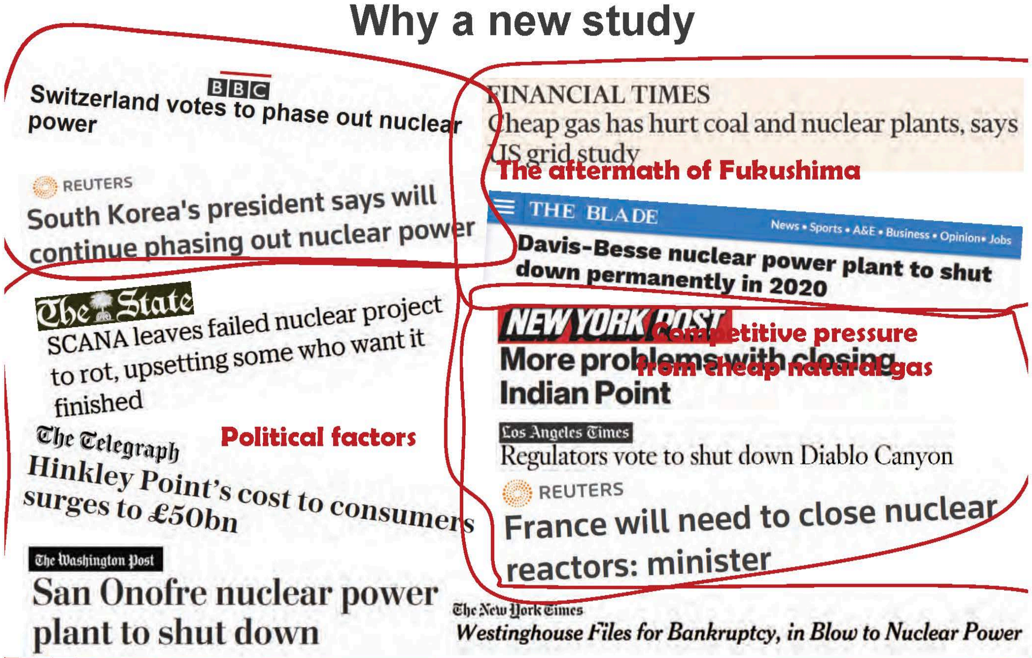
- The opportunity is carbon
- The problem is cost
- There are ways to reduce it
- Government's help is needed to make it happen

Download the report at
http://energy.mit.edu/



Hard copies of the Executive Summary available in the room

Why a new study



The nuclear industry's Self-inflicted wounds facing an existential crisis (especially in the U.S. and Europe)

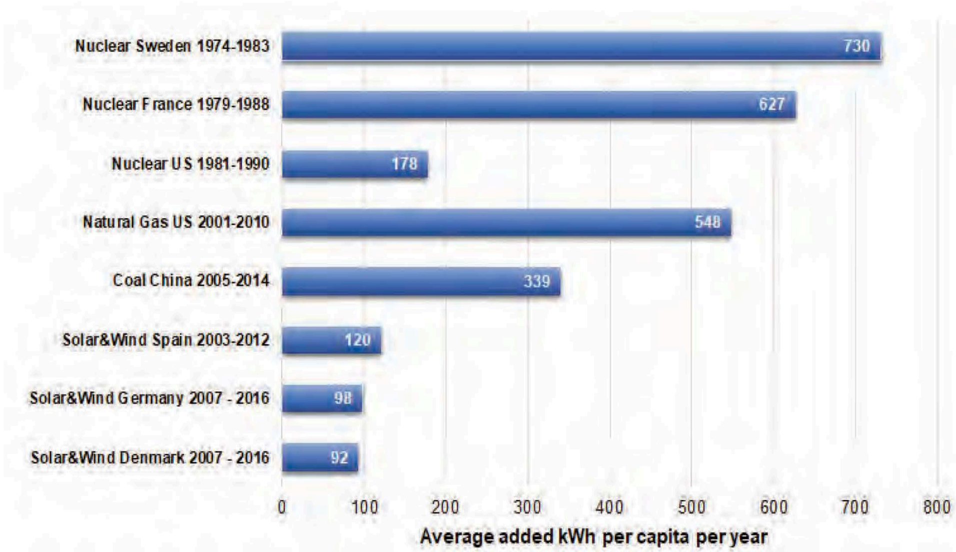
Key Questions Analyzed in the MIT Study

For the period present-2050:

- Do we need nuclear to de-carbonize the power sector?
- What is the cost of new nuclear and how to reduce it?
- What is the value proposition of advanced nuclear technologies?
- What is the appropriate role for the government in the development and demonstration of new nuclear technologies?

What role for nuclear in decarbonizing the power sector?

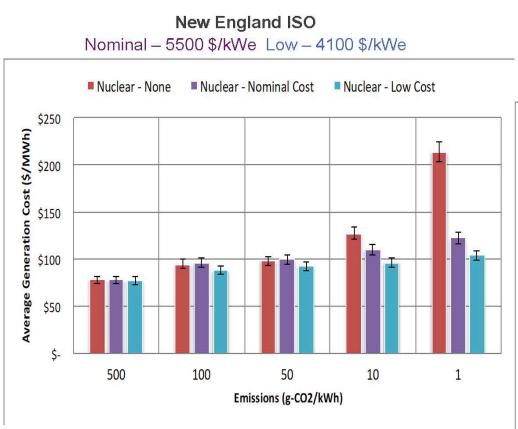
The scalability argument

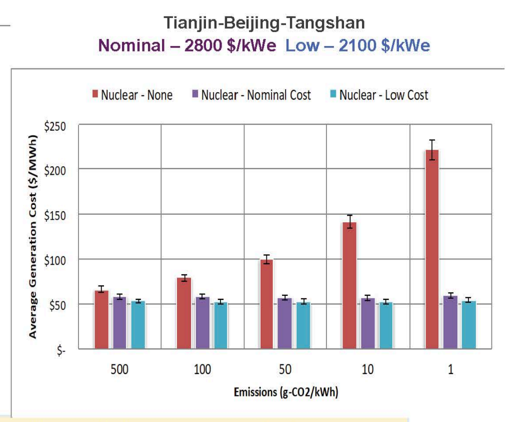


Nuclear electricity can be deployed as quickly as coal and gas at a time of need

The economic argument

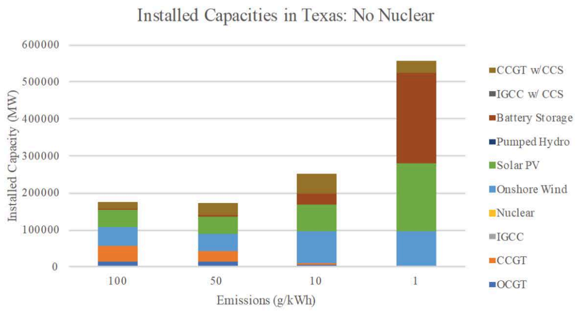
Excluding nuclear energy drives up the cost of electricity in low-carbon scenarios (U.S., Europe and China)





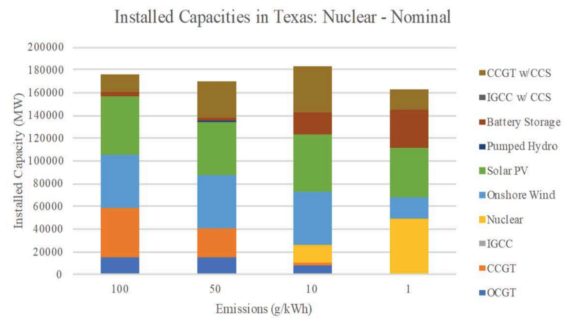
Simulation of optimal generation mix in power markets
MIT tool: hourly electricity demand + hourly weather patterns + capital, O&M and fuel costs of power plants, backup and storage + ramp up rates

Texas (ERCOT) Results

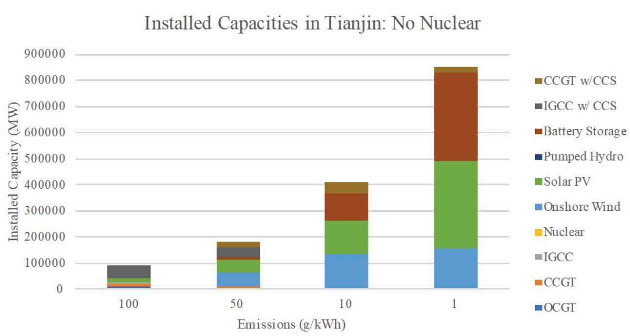


To meet constraint w/o nuclear requires major build-out of renewables

By contrast, installed capacity is relatively constant with nuclear allowed

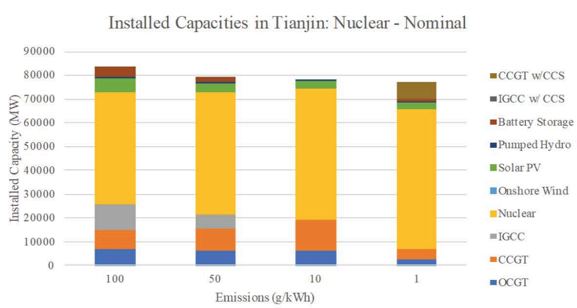


Tianjin-Beijing-Tangshan Results

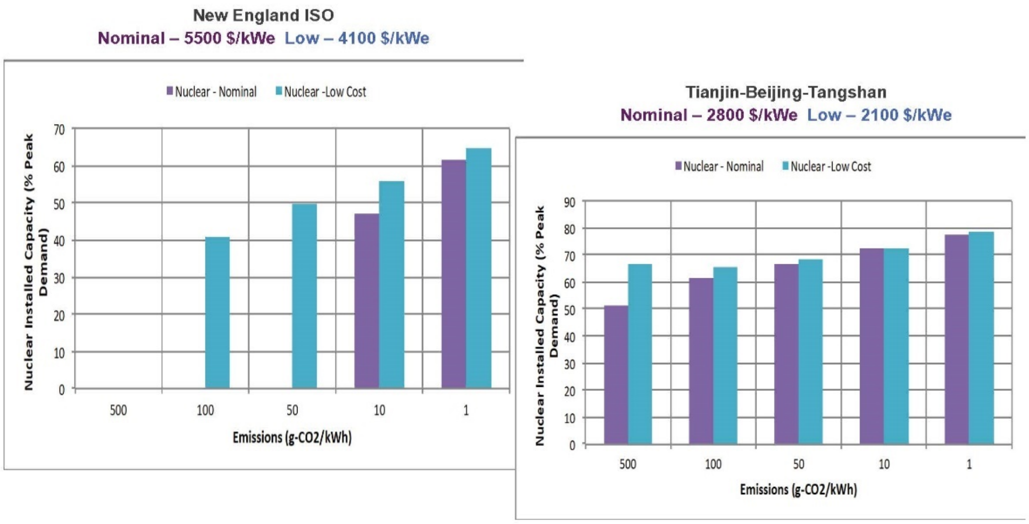


To meet constraint w/o nuclear requires significant build-out of renewables

By contrast, installed capacity is relatively constant with nuclear allowed



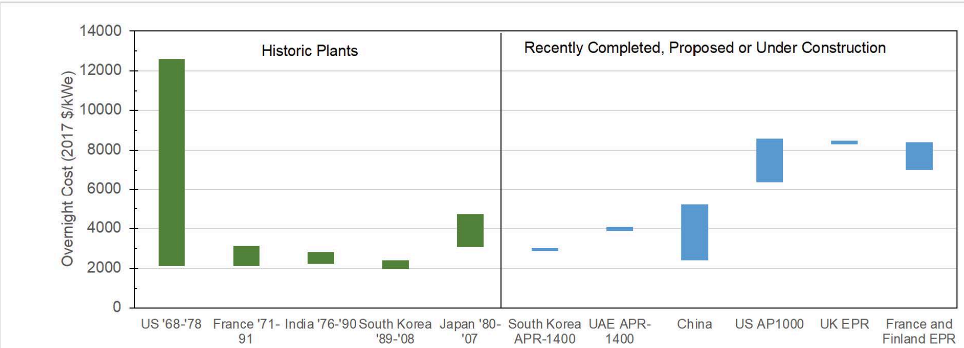
Capital cost matters!



Markets can expand for nuclear even at modest decarbonization

The cost issue

Nuclear Plant Cost

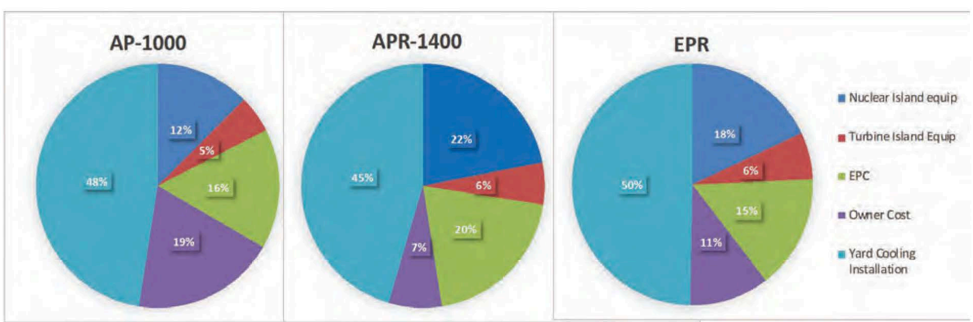


An increased focus on using proven project/construction management practices will increase the probability of success in execution and delivery of new nuclear power plants

For example:

- Complete design before starting construction,
- Develop proven NSSS supply chain and skilled labor workforce,
- Include fabricators and constructors in the design team,
- Appoint a single primary contract manager,
- Establish a successful contracting structure,
- Adopt a flexible contract administrative processes to adjust to unanticipated changes,
- Operate in a flexible regulatory environment that can accommodate changes in design and construction in a timely fashion.

Nuclear Plant Cost (2)



Sources:
AP1000: Black & Veatch for the National Renewable Energy Laboratory, *Cost and Performance Data for Power Generation Technologies*, Feb. 2012, p. 11
APR1400: Dr. Moo Hwan Kim, POSTECH, personal communication, 2017
EPR: Mr. Jacques De Toni, Adjoint Director, EPRNM Project, EDF, personal communication, 2017

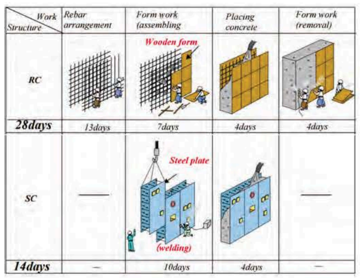
Civil works, site preparation, installation and indirect costs (engineering oversight and owner's costs) dominate

A shift away from primarily field construction of cumbersome, highly site-dependent plants to more serial manufacturing of standardized plants
(True for all plants and all technologies. Without these, the inherent technological features will NOT produce the level of cost reduction necessary)

Standardization on multi-unit sites

Seismic Isolation

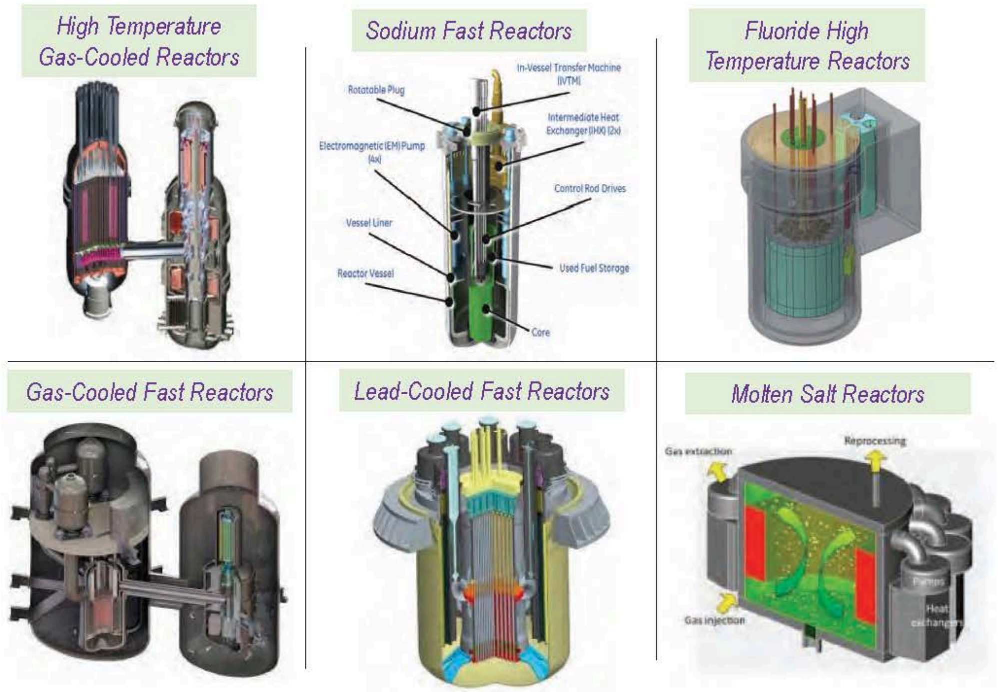
Advanced Concrete Solutions



Modular Construction Techniques and Factory Fabrication

Advanced reactors

Advanced Reactors (Generation-IV)



Potential Advanced Reactor Missions

- Cheap grid-connected electricity
- Process heat and high temperature applications
- Flexible operation
- Microreactors for off-grid electricity and heat
- Desalination
- Improved fuel cycle (fuel recycling/waste burning)

What is the value proposition for advanced reactors?

Demonstrated inherent safety attributes:

- No coolant boiling
- High thermal capacity
- Strong negative temperature/power coefficients
- Strong fission product retention in fuel, coolant and moderator
- Low chemical reactivity

\+

Engineered passive safety systems:

- Heat removal
- Shutdown

Active Safety Systems

=

- ✓ No need for emergency AC power
- ✓ Long coping times
- ✓ Simplified design and operations
- ✓ Emergency planning zone limited to site boundary

Leading Gen-IV systems exploit inherent and passive safety features to reduce the probability of accidents and their offsite consequences. Their economic attractiveness is still highly uncertain.

We judge that advanced LWR-based SMRs (e.g. NuScale), and mature Generation-IV concepts (e.g., high-temperature gas-cooled reactors and sodium-cooled fast reactors are now ready for commercial deployment.

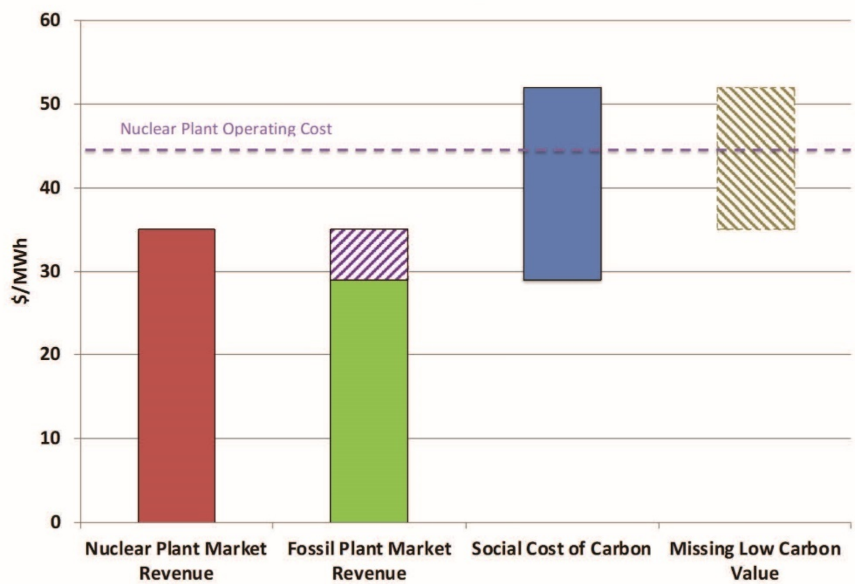
Government role

Preserve the existing fleet

An essential bridge to the future to:

- **Avoid emission increases:**
  - Keeping current NPPs is the lowest cost form of constraining carbon emissions
  - A $12-17/MWh credit would be enough to keep US nuclear power plants open
  - *Zero Emission Credits* are doing the job in NY, IL and NJ
- **Retain key technical expertise** needed to operate the nuclear systems of the future

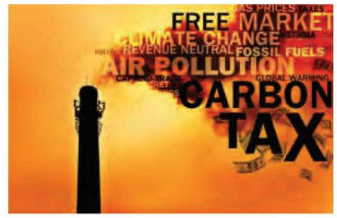
US Electricity Markets



How can the government help to deploy new nuclear technologies?

Improve the design of competitive electricity markets

- Decarbonization policies should create a level playing field that allows all low-carbon generation technologies to compete on their merits.
- Ensure technology neutrality in capacity markets
- Enable investors to earn a profit based on full value of their product (include reducing CO2 emissions)
- Would enable current plants to compete in the market

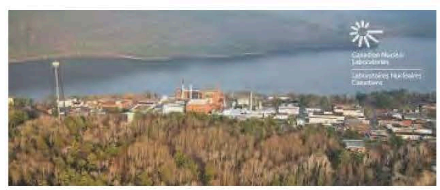


- Develop a durable political solution for spent fuel disposal to spur private investment
- Focus government research spending on innovations that lower capital cost of NPPs vs. fuel cycle innovations, reductions in waste streams and recycling

How can the government help to deploy new nuclear technologies? (2)

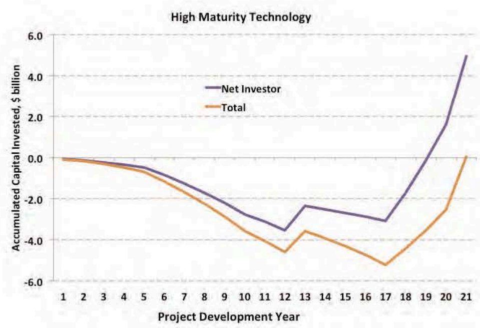
Governments should establish reactor sites where companies can deploy prototype reactors for testing and operation oriented to regulatory licensing.

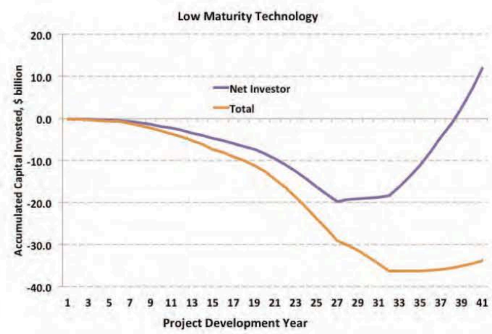
- Government provides site security, cooling, oversight, PIE facilities, etc.
- Government provides targeted objectives, e.g. production of low-cost power or industrial heat, for which it is willing to provide production payments as an incentive
- Government takes responsibility for waste disposal
- Companies using the sites pay appropriate fees for site use and common site services
- Supply high assay LEU and other specialized fuels to enable tests of advanced reactors



How can the government help to deploy new nuclear technologies? (3)

High upfront costs and long time to see return on investment (more so for less mature technologies, e.g. FHR, MSR, LFR, GFR, than more mature technologies, i.e. HTGR, SFR)



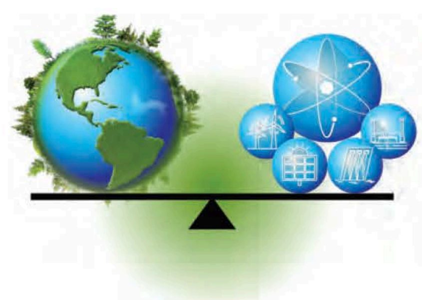


Early government support helps. Four "levers":

- Share R&D costs
- Payments for construction milestones
- Share licensing costs
- Production credits

Take-away messages

- **The opportunity is carbon**
- **The problem is cost**
- **There are ways to reduce it**
- **Government's help is needed to make it happen**

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Acknowledgements
This study is supported by generous grants and donations from
ALFRED P. SLOAN FOUNDATION 1934
eDF
the David & Lucile Packard FOUNDATION
GENERAL ATOMICS
Anthropocene Institute
Neil Rasmussen
James Del Favero
Zach Pate
and in-kind contributions from
INL Idaho National Laboratory
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Nuclear Cost Drivers Project

Presentation to the EPRI / GAIN / NEI
Workshop on Economics-Based R&D for
Nuclear Power Construction

January 17-18, 2019

Contents

- Project Overview
- Methodology
- Findings
- Conclusions
- Recommendations

Project Objectives

- Perform and report an analysis of the principal cost drivers for contemporary designs, SMRs and advanced reactor technologies
- Assemble a credible cost database and associated cost model for the purposes of the Project and ultimately use by the ETI, the ETI Members, and (at the ETI's discretion) other third parties
- Identify areas of nuclear power plant design, construction and operation with potential to deliver cost reduction relevant to contemporary designs, advanced reactor technologies and SMRs

3

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- Project Overview
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- Conclusions
- Recommendations

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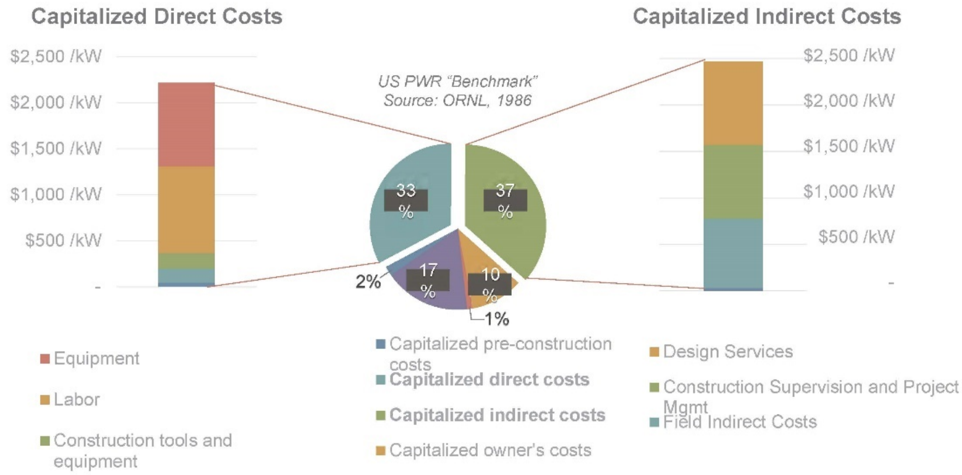
Cost breakdown of typical plant

- cost breakdown of typical well documented plant to demonstrate that capital cost and cost of capital dominate



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Methodology

- Methodology designed around existing and expected constraints
  - Lack of publicly-available data
  - Confidential/Proprietary nature of cost information
  - Concern with obtaining cost rationale not only costs
  - Limited time and budget but with a global scope
- Project is not intended to predict project costs but to identify trends

*Performed regression analysis on cost drivers to estimate relative influence on total project cost. Regression coefficients were used in the interactive cost model.

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Identifying Cost Drivers to Analyse

- Project team held several internal collaborative workshops and extensive consultations with the ETI, the independent reviewer, and other cost experts
- Arrived at 8 cost drivers:

Cost Drivers
1. Vendor Plant Design
2. Equipment and Materials
3. Construction Execution
4. Labour
5. Project Development and Governance
6. Political and Regulatory Context
7. Supply Chain
8. Operations

Each driver has detailed quantitative and qualitative components

Cost Driver Indicators (Example)

Vendor Plant Design
Responsible Party: Reactor Vendor
Plant capacity
Previous units in same country
Previous units elsewhere in world
Thermal efficiency
Plant complexity
Safety systems
Seismic design
System and equipment redundancy
System and equipment complexity
Design tools - 3D CAD? 4D CAD?
Design for reusability

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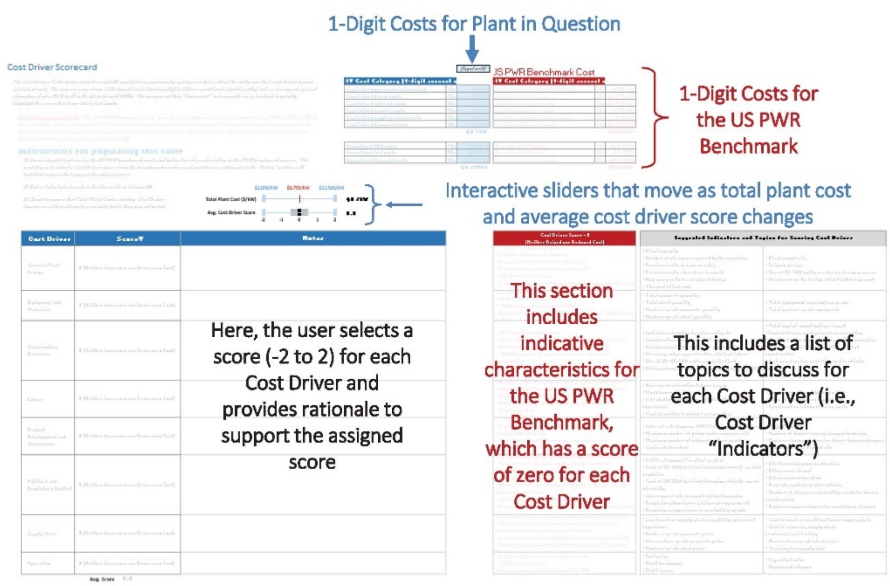
Cost driver Scorecard



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ETI Cost Model

Cost Model Dashboard

Select genre --> Conventional in Europe / North Am

Scenario name --> Example scenario name

Save Scenario to Archive

Cost Estimates Based on Cost Driver Settings (Below) and Regression Coefficients

			Reference US PWR	Conventional in Europe / North Am		
				Representative Cost	Change from Represent. Cost	Updated Cost With Change
Capital	10s	Preconstruction Costs	$133 /kW	$179 /kW	-	$179 /kW
	20s E	Direct Construction Costs: Equipment	$1,006 /kW	$1,354 /kW	-	$1,354 /kW
	20s M	Direct Construction Costs: Materials	$292 /kW	$393 /kW	-	$393 /kW
	20s L	Direct Construction Costs: Labour	$957 /kW	$1,287 /kW	-	$1,287 /kW
	30s	Indirect Services Costs	$2,512 /kW	$3,379 /kW	-	$3,379 /kW
	40s	Owner's Costs	$715 /kW	$962 /kW	-	$962 /kW
	50s	Supplementary Costs	$79 /kW	$106 /kW	-	$106 /kW
	60s	Financing During Construction	$1,175 /kW	$2,794 /kW	-	$2,794 /kW
		Total Construction Costs	$6,870 /kW	**$10,454 /kW**	-	**$10,454 /kW**
		Levelised Construction Costs	$59 /MWh	**$89 /MWh**	-	**$89 /MWh**
Operating	70s	O&M Costs	$21 /MWh	$14 /MWh	-	$14 /MWh
	80s	Fuel Costs	$7 /MWh	$10 /MWh	-	$10 /MWh
	90s	Financing During Operation	$0 /MWh	$0 /MWh	-	$0 /MWh
		Total Operating Costs	$28 /MWh	**$25 /MWh**	-	**$25 /MWh**
		Levelised Cost of Electricity	$87 /MWh	**$114 /MWh**	-	**$114 /MWh**

Cost Driver Settings

	Reference US PWR	Conventional in Europe / North Am		
		Representative Value	Cost Driver Sliders	User's Updated Value
Generic Plant Design - Vendor	0.0	+2.0		+2.0
Equipment and Materials - EPC/Vendor	0.0	+1.8		+1.8
Construction Execution - EPC	0.0	+1.4		+1.4
Labour - EPC	0.0	+1.4		+1.4
Project Development and Governance - Owner	0.0	+1.2		+1.2
Political and Regulatory Context - Government	0.0	+1.0		+1.0
Supply Chain - Vendors	0.0	+1.8		+1.8
Operation - Owner	0.0	+0.4		+0.4
Average	0.0	+1.4		+1.4

Cost driver settings can range from -2 (significant cost reduction) to +2 (significant cost increase); 0 corresponds to PWR Reference

Click on scroll bar arrows to adjust cost driver settings

Breadth and extent of expert interviews

- Most nuclear cost studies attempt to get data on costs, which is difficult and cost data is not particularly reliable. We wanted to get around this by getting detailed story for each unit in our database using our scorecard and cost driver analysis.
- Team triangulated with multiple sources (where possible) for each scorecard. Interviewed 30 organisations (many of whom we met multiple times)
- >150 hours of interviews
- Experts included:
  - Construction Managers
  - Chief Project Officers
  - Board-level Directors
  - Regulators
  - Infrastructure project mgrs
  - Global nuclear new build mgrs
  - Project Directors
  - Quality Assurance experts
  - Contract lawyers
  - Senior Policy Directors
  - Government policymakers
  - Senior Management at vendor companies
- Interviewees from: Japan, Korea, France, US, UK, Sweden, Russia, Finland, India

Methodological assumptions

- Key supporting assumptions include:
  - Plants are compared on an apples-to-apples basis by adding IDC (interest during construction)
  - Common interest rate of 7%
  - Standardised fuel cost
  - Depreciation period of 60 years (consistent with BEIS LCOE methodology for new power plants)
  - Same interest rate during operations phase as per construction phase
  - Capacity factor of 95%

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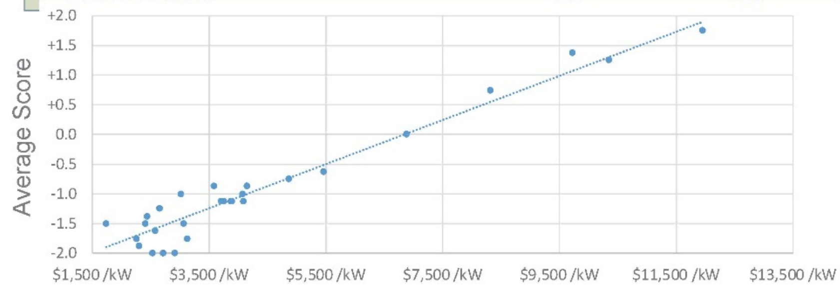
Broad range of cost and scores

Data used in Analysis

Genre	# of Units in CTC-Lucid	# of Units in ETI Database
US PWR Benchmark	1	*1*
North America & Europe	5	*5*
Rest of World	28	*28*



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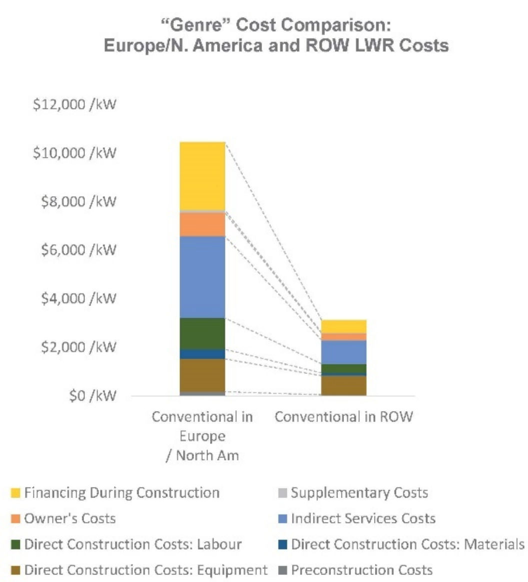
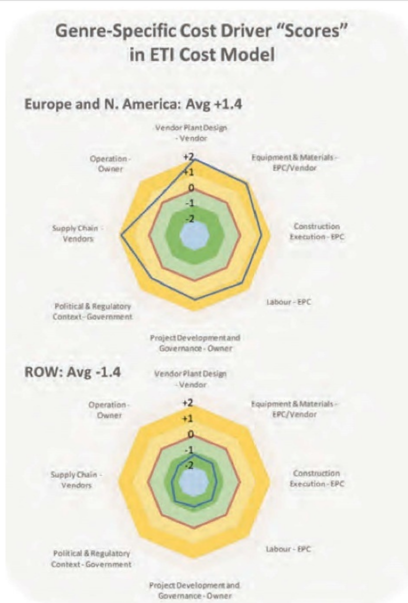
LWR "genre" costs: EU/N. America vs. ROW





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Common characteristics

Common characteristics of low-cost and high-cost projects

Low Cost Plants	High Cost Plants
• Design at or near complete prior to construction • High degree of design reuse • Experienced construction management • Low cost and highly productive labour • Experienced EPC consortium • Experienced supply chain • Detailed construction planning prior to starting construction • Intentional new build programme focused on cost reduction and performance improvement • Multiple units at a single site • NOAK design	• Lack of completed design before construction started • Major regulatory interventions during construction • FOAK design • Litigation between project participants • Significant delays and rework required due to supply chain • Long construction schedule • Relatively higher labour rates and low productivity • Insufficient oversight by owner

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Case studies

- Sizewell B and Nuclear Electric's proposal for Sizewell C
- Barakah 1-4
- Vogtle 3 & 4
- Rolls Royce SMR
- Japan Atomic Energy Agency's High Temperature Engineering Test Reactor
- Molten Salt Reactor (generic)
- Offshore Wind

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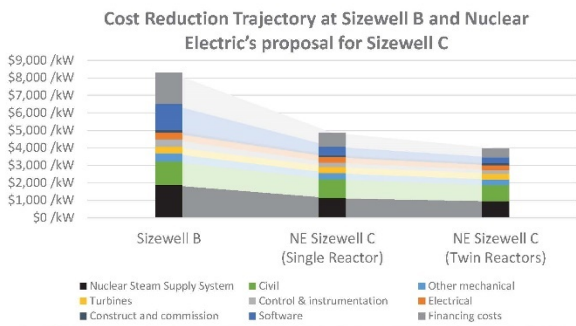
Learnings from Sizewell B

30% reduction in overnight costs from Sizewell B to Nuclear Electric's proposal for Sizewell C (single reactor)



	Cost Reductions from Sizewell B	
Capital Costs	**Sizewell C Single**	**Sizewell C Twin**
Nuclear Steam Supply System	$752 /kW	$935 /kW
Civil	$271 /kW	$419 /kW
Other mechanical	$103 /kW	$147 /kW
Turbines	$38 /kW	$44 /kW
Control & instrumentation	$185 /kW	$224 /kW
Electrical	$53 /kW	$100 /kW
Construct and commission	$23 /kW	$35 /kW
Software	$1,008 /kW	$1,146 /kW
Financing costs	$1,041 /kW	$1,302 /kW
Total Cost Reductions	**$3,475 /kW**	**$4,352 /kW**

- Savings based on contractually-bound estimates for Nuclear Electric's proposal for Sizewell C

*Nuclear Electric plc paid expenditures for Sizewell B with income from other nuclear plants without incurring significant debt. We estimated financing costs for Sizewell B (as well as the Sizewell C configurations) for consistency with financing calculations for other plants in the database.

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Cost reduction through learning

- Use of same contractors, vendors, and labour
- Regulators experienced with the design and delivery team (fewer expected changes)
- 30% reduction in schedule duration
- 40% overall cost reduction (with assumed financing)
- Twin units reflect sequenced delivery to optimise labour and construction schedule

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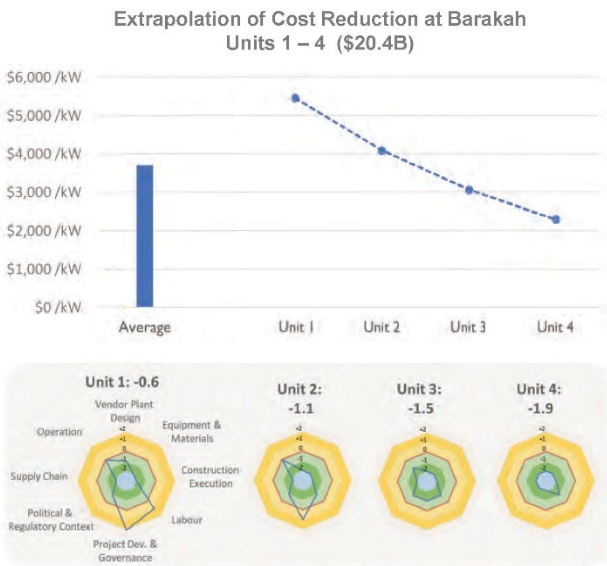
Barakah: benefits of a multi-unit programme



- Programme incorporates best practices in all cost driver categories
- Commitment to 4-unit purchase
  - Building on successful multi-unit builds in Korea
  - Same contractors and suppliers
  - Economies of scale in equipment procurement
- Exceptional project governance
  - Purchased plants in a way that allowed vendor to optimise process/ sequence, build continuously, maintain skills and experience
  - Fixed price project with significant success fee tied to on-time delivery
  - KEPCO was free to modify schedule but not delivery date
- RfP and bidding process preceded by comprehensive "lessons learned" study

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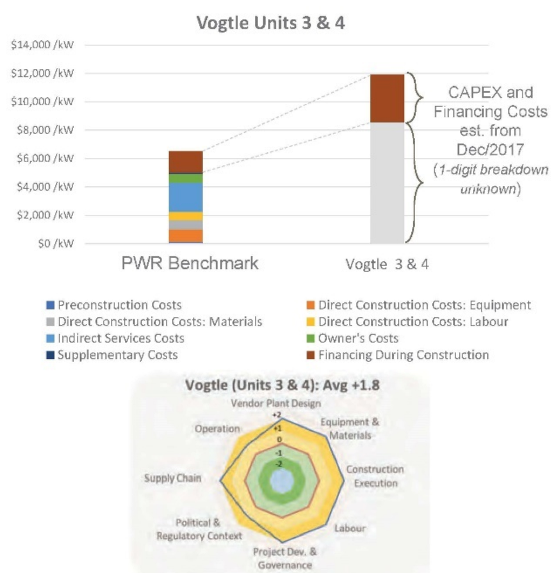
Vogtle Units 3 & 4



- Started construction well before design was complete (precluded meaningful/ detailed construction planning)
- FOAK design
- Extreme lack of experience in supply chain and labour force
- Poor QC of modules manufactured offsite
- Project is now 68 months beyond initial COD target, escalating financing costs.
- Numerous construction setbacks
- Complicated contracting and poor liability assignment (reactor vendor eventually bought prime contractor to end lawsuits between both parties)

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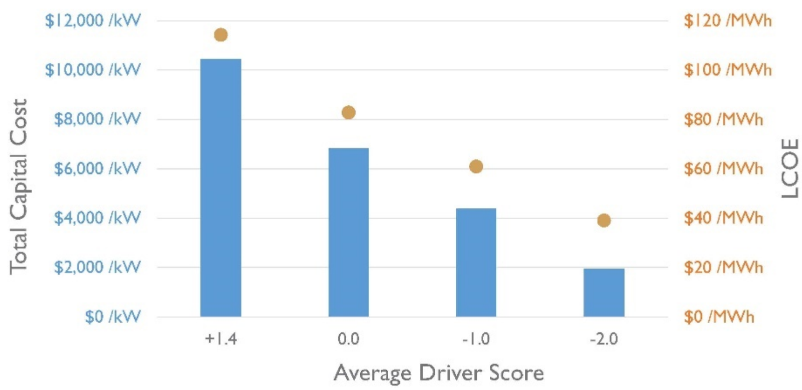
Cost Reduction Scenarios for EU/US Genre



Alternative Cost Scenarios with Other Rate Assumptions

Avg.			7%		6%		9%	
Score	Capex/kW	Opex	Capex/MWh	LCOE	Capex/MWh	LCOE	Capex/MWh	LCOE
+1.4	$10,454 /kW	$25 /MWh	$89 /MWh	$114 /MWh	$75 /MWh	$99 /MWh	$123 /MWh	$148 /MWh
0.0	$6,826 /kW	$24 /MWh	$58 /MWh	$83 /MWh	$48 /MWh	$72 /MWh	$84 /MWh	$108 /MWh
-1.0	$4,386 /kW	$23 /MWh	$38 /MWh	$61 /MWh	$29 /MWh	$53 /MWh	$57 /MWh	$81 /MWh
-2.0	$1,946 /kW	$22 /MWh	$17 /MWh	$39 /MWh	$11 /MWh	$34 /MWh	$31 /MWh	$53 /MWh

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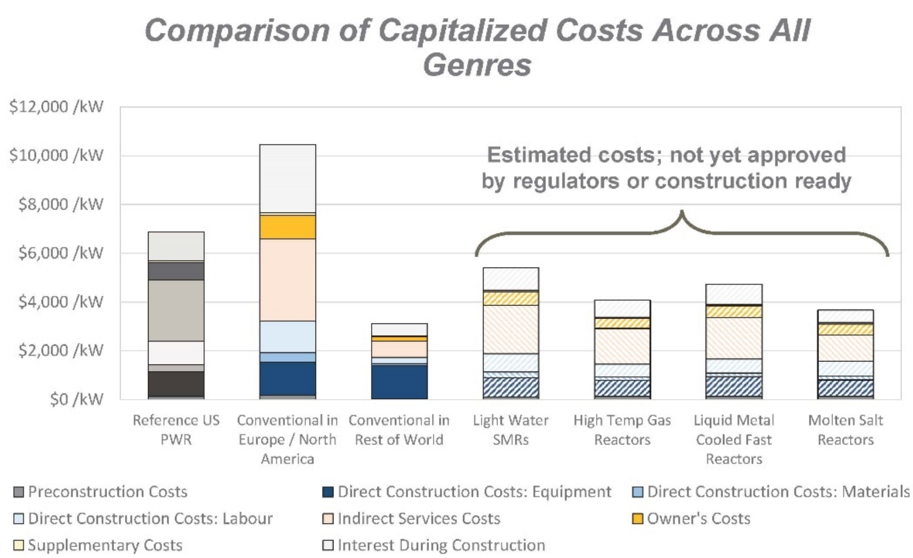
Genre summary results (CAPEX)



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Genre summary results (LCOE)

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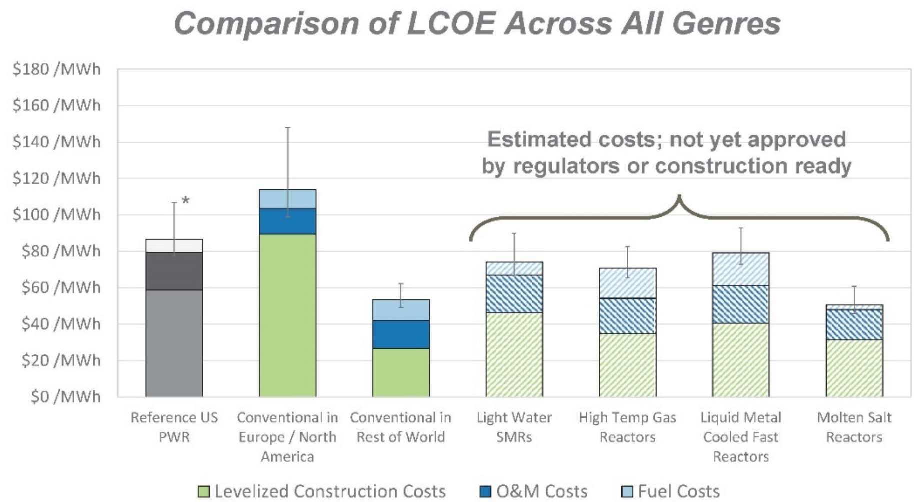

* Boxplot whiskers represent LCOE at 6% and 9% Interest During Construction

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Correlations: Incomplete design = high costs

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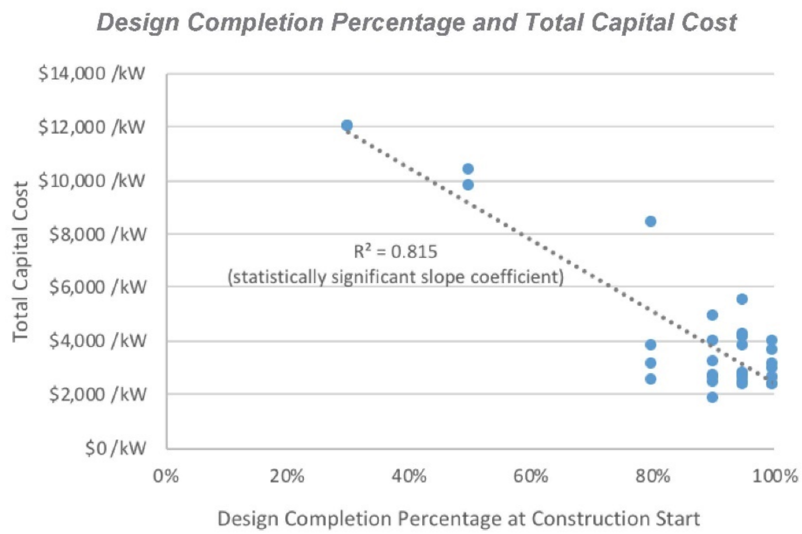

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Conclusions (1 of 3)

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- A relatively small number of understandable factors drives the cost of nuclear plants. Whilst building nuclear plants takes place through large, complex projects, the findings of this study are straightforward and there was a high degree of consensus among the experts consulted
- Strong evidence of applicable cost reduction in the UK
- Fleet deployment by itself does not necessarily guarantee cost reduction
- Relatively significant cost reduction is possible outside reducing the cost of capital during construction
- Larger Gen III/III+ reactors and light-water SMRs are more market-ready than advanced reactors

Conclusions (2 of 3)

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- Cost reduction and more predictable delivery can reduce perceived risk and potentially lower the cost of interest during construction (reducing CapEx even further)
- The cost reductions in "Rest of World" LWRs are a consequence of national nuclear programmes and the consistent, rational implementation of best practices
- Project delivery organizations in China, Korea, and Japan allocate adequate resources toward maintaining constant efficiency improvements in plant delivery
- Recent challenges in North America and Europe new build projects are partially attributable to local "context."

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Conclusions (3 of 3)

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- Within the 35 cost reduction opportunities identified in this study, the Project Team identified a smaller group of actions that present the best opportunities for reducing project cost and risk in the UK. This group of actions is strongly supported by the evidence base, interviews, and regression analysis

Finding	Cost Driver Category
o Complete plant design prior to starting construction	(Vendor Plant Design)
o Follow contracting best practices	(Project Dev. & Governance)
o Project owner should develop multiple units at a single site	(Project Dev. & Governance)
o Innovate new methods for developing alignment with labour around nuclear projects	(Labour)
o Government support should be contingent on systematic application of cost reduction measures	(Political and Regulatory Context)
o Design a UK programme to maximize and incentivize learning, potentially led by a newly-created entity	(Political and Regulatory Context)
o Government must play a role in supporting financing process	(Political and Regulatory Context)
o Transform regulatory interaction to focus on cost-effective safety	(Political and Regulatory Context)

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The historical construction cost and cost drivers of nuclear power plants

Dr. Francesco Ganda (ANL)

EPRI NEI GAIN workshop on Construction Economics

January 17-18 at NEI, Washington DC

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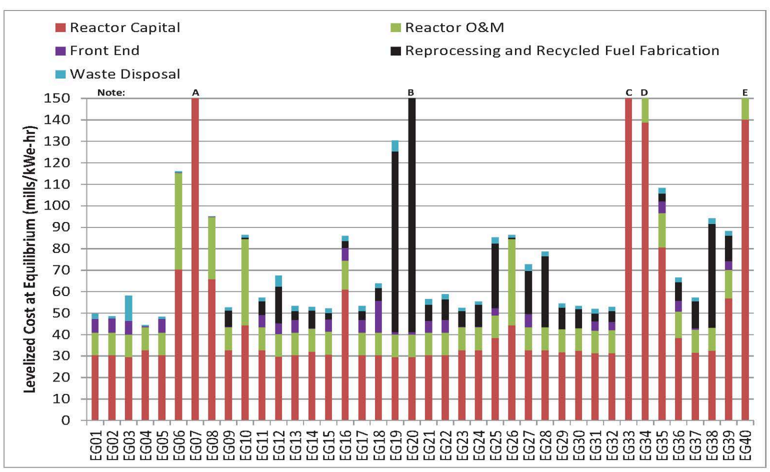
The biggest LCOE driver

– The Reactor Capital Cost and the Reactor Operation & Maintenance (O&M) costs dominate the overall LCOE.



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Historical construction costs for LWR in the US

– Early reactors had low overnight costs, short construction times and limited cost overruns

Name of reactor	MW		State	Start constr	End constr	**Years for construction**	Lifetime	th. Efficiency	**Overnight capital cost (2018 $)**	TOT capital cost (2018 $)
Palisades	697	PWR	MI	3/15/1967	12/31/1971	**4.8**	40	32.90%	**889.76**	**998.3**
Vermont Yankee	507	BWR	VT	12/12/1967	11/30/1972	**5**	40	33.70%	**1857.24**	**2091.74**
Maine Yankee	879	PWR	ME	10/22/1968	6/29/1973	**4.7**	23.4	32.50%	**1425.76**	**1591.92**
Pilgrim	672	BWR	MA	8/27/1968	12/2/1972	**4.3**	40	33.50%	**1823.74**	**2011.34**
Surry 1	790	PWR	VA	6/26/1968	12/22/1972	**4.5**	40	33.90%	**1180.54**	**1310.52**
Turkey Point 3	672	PWR	FL	4/28/1967	12/14/1972	**5.6**	40	31.00%	**765.14**	**879.04**
Surry 2	793	PWR	VA	6/26/1968	5/1/1973	**4.8**	40	33.90%	**1180.54**	**1325.26**
Oconee 1	851	PWR	SC	11/7/1967	7/15/1973	**5.7**	40	32.80%	**818.74**	**943.36**
Turkey Point 4	673	PWR	FL	4/28/1967	9/2/1973	**6.4**	40	31.00%	**765.14**	**899.14**
Prairie Island 1	511	PWR	MN	6/26/1968	12/16/1973	**5.5**	40	31.80%	**1811.68**	**2071.64**
Zion 1	1069	PWR	IL	12/27/1968	10/19/1973	**4.8**	23.3	32.50%	**1222.08**	**1370.82**
Fort Calhoun	478	PWR	NE	6/8/1968	9/26/1973	**5.3**	40	32.10%	**1922.9**	**2186.88**
Kewaunee	521	PWR	WI	8/7/1968	6/16/1974	**5.9**	40	31.00%	**1687.06**	**1952.38**
Cooper	764	BWR	NE	6/6/1968	7/2/1974	**6.1**	40	31.80%	**1606.66**	**1871.98**
Peach Bottom 2	1078	BWR	PA	2/1/1968	7/2/1974	**6.4**	40	32.40%	**1618.72**	**1905.48**
Browns Ferry 1	1026	BWR	AL	5/11/1967	7/31/1974	**7.2**	11.4	32.70%	**1072**	**1294.44**
Oconee 2	851	PWR	SC	11/7/1967	9/9/1974	**6.8**	40	33.10%	**818.74**	**976.86**
Three Mile Island 1	790	PWR	PA	5/19/1968	9/2/1974	**6.3**	40	30.60%	**2115.86**	**2481.68**
Zion 2	1001	PWR	IL	12/27/1968	11/14/1973	**4.9**	22.8	32.50%	**1222.08**	**1373.5**
Arkansas 1	836	PWR	AR	12/7/1968	12/19/1974	**6**	40	30.80%	**1192.6**	**1388.24**
...	...	...	...	...	...	...	...	...	...	...

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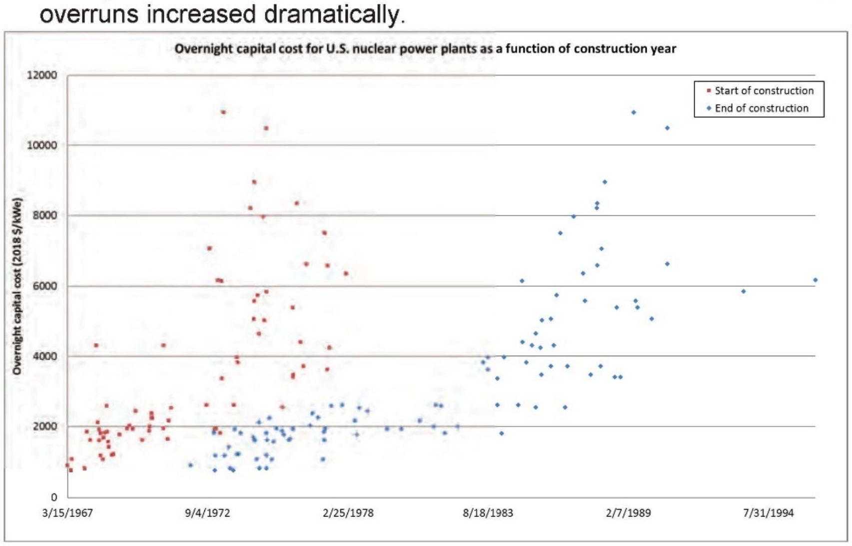
Historical construction costs for LWR in the US

– During the '70s and '80s construction costs, construction time and cost overruns increased dramatically.



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Understanding reactor capital costs

- A key objective:
  - *Establish a framework for understanding the reasons for the observed historical capital costs*
- Identify:
  - *The fundamental drivers of cost,*
  - *The reasons of the biggest cost overruns observed historically.*
- Distinction between:
  - *Cost of "best experience" in reactor construction;*
  - *Cost overruns.*
- Most of the literature on the subject mostly take, at best, an observational approach, with mathematical attempts to interpolate, and sometimes extrapolate, from historical data.
- Single construction cost drivers are not easy to identify, contrary to the case of coal plants, for example: in the '70s, the addition of scrubbers, and particulate abatement equipment, measurably increased the cost of construction.

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The main cause for the over budget constructions

- A key driver of cost overruns during construction is the degree of design changes requested during the construction phase:
  - *Incomplete engineering at the start of construction;*
  - *Regulatory turbulence.*
- If design is fully completed before the construction starts and no changes are requested during the construction phase, complex construction projects can be kept reasonably within budget:
  - *Fixed price contracts, negotiated with competitive bidding: minimize the construction costs and keep the project within budget.*
- If design changes significantly during the construction phase, the original fixed price contracts become un-tenable and re-bidding is usually impractical:
  - *Fixed price contracts have to be switched to "cost plus" contracts and efficiencies are lost.*

F. Ganda, T. K. Kim, T. A. Taiwo and R. Wigeland, "Analysis of reactor capital costs and correlated sampling of economic input variables", Proceedings of ICAPP 2015, May 03-06, 2015, Nice (France), Paper 15342.

F. Ganda, J. Hansen, T. K. Kim, T. A. Taiwo, R. Wigeland, "Reactor Capital Costs Breakdown And Statistical Analysis Of Historical U.S. Construction Costs", Proceedings of ICAPP 2016, April 19th, 2016, San Francisco, CA, Paper 16829.

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Changes during construction

– Changes during construction affect cost overruns:
  - *Completed work has to be removed/altered, often with "ripple effects" on nearby systems;*
  - *Construction sequences has to be altered, and equipment delivery schedules has to be altered, potentially idling groups of workers → lower labor productivity;*
  - *Increased construction duration can create a positive feed-back loop by exposing the project to increased risk of regulatory turbulence; increasing interest costs and disrupting construction logistics.*

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A case study: the Davis Besse power station

– Construction approved by the board of Toledo Edison in December 1967, for \$136 million (\$1 billion in 2018 \$), for 800 MW_e on the shores of Lake Erie → 1300 $\$_{2013}/kW_e$.

– Completion expected for 1974. When completed in 1977, the final cost was \$650 million (\$2.7 billion in 2018 \$) for 906 MW_e → 3000 $\$_{2018}/kW_e$.

– Originally expected to reduce utility bills in Ohio, at completion it added 19% to the average utility bill because of costs overruns.

– Christopher Bassett, then with the Ohio Public Utilities Commission, published a paper quantifying the details of the cost escalation:
C. Bassett, "The high cost of Nuclear Power Plants", Public Utilities Fortnightly, April 1978.

– Addition of a cooling tower, at the request of the Ohio Water Pollution Control Board, and an increase in power output from 800 to 906 MW_e were commonly associated with the cost escalation. Not significant after close examination.

– Some contracts were tied to escalation (while others were lump sum bidding): during a period of high inflation this was believed to be a main source of cost escalation. Not dominant after quantification.

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A case study: the Davis Besse power station

– Summary table of construction cost increases for Davis Besse:

TABLE 1
DAVIS-BESSE UNIT NO. 1
ANALYSIS OF CONSTRUCTION
COST INCREASES

		Thousands of Dollars	
Original Appropriation — 12/26/67		$136,000	21%
Unit Size Increase 800 Mw to 906 Mw		18,000	3%
Inflation in Labor and Materials		86,000	13%
Cooling Tower Addition		11,000	2%
Higher Land Cost for Restoration of Marshlands		1,000	0%
NRC Modifications and Their Chain Effects			
· design modifications	$195,000		
lost of productivity due to retrofitting the above changes	72,000		
increase in AFDC charges due to construction delays and cost increments for above changes	110,000		
greater cost for training and acceptance	21,000		
		398,000	61%
Ultimate Total Project		$650,000	100%

Because effects are very intertwined, the table is approximate:
For example: AFDC charges were increased by an increase in allowable FPC (FERC) AFDC rates from 6.5% to 8% during the project life, but this was a small effect compared to the effects of delays caused by the changes in regulatory requirements.

From: Bassett C. (1978), "The high cost of nuclear power plants", April 27, 1978, Public Utilities Fortnightly.

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A case study: the Davis Besse power station

– Large escalation was observed for "Piping and Mechanical", "Civil and Structural", "Architect-Engineer" and "Electric", all intensively labor oriented where retrofitting had a large impact.

– In contrast, contracts which involved relatively fixed pieces of hardware (e.g. "steam supply system", "turbine generators", "cooling towers", and "containment vessel") did not experience substantial escalation: retrofits had limited impact on those procurement costs. (About 50% of original cost, before escalation).

TABLE 2
DAVIS-BESSE UNIT NO. 1
TEN OF THE LARGEST CONSTRUCTION CONTRACTS

Contract	Low Bid	Hight Bid ($ in Thousands)	Ultimate Amount Paid Out
Piping and Mechanical	$14,822	$18,470	$ 79,940
Civil and Structural	10,672	11,485	67,235
Architect-engineer	7,821	7,821	46,310
Electrical	4,900	8,711	43,890
Steam Supply	28,745	33,981	39,960
Turbine-Generator	22,259	22,259	24,073
Instrumentation	4,016	4,449	14,507
Cooling Tower	8,380	9,964	7,571
Containment Vessel	5,980	5,980	6,583
Concrete	1,639	2,559	3,550
Total			$330,619

From: Bassett C. (1978), "The high cost of nuclear power plants", April 27, 1978, Public Utilities Fortnightly.

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A case study: the French construction program

- The French construction program benefited from:
  - *Rigorous cost control and planning by EDF (which acted as Architect Engineer).*
  - *Engineering stability*
    - "*Whenever an engineer had an interesting or even genius [improvement] idea either in-house [EDF] or at Framatome, we said: OK, put it on file, this will be for the next series, but right now, we change nothing.*" Boiteux, CEO of EDF, 2009 [b].
  - *Regulatory stability*
    - *There are no documented regulatory incidences from 1970 to 1999* [a]*;*
    - *The "Authorité de Sureté Nucléaire" (ASN, the independent regulatory agency) was created in 2006, 4 years after the last reactor was completed in 2002* [a]*;*
    - *EDF, despite the stability of safety rules, integrated progressively more stringent safety features in new reactors* [a]*.*

[a] *L. Rangel, F. Leveque, "Revisiting the Cost Escalation Course of Nuclear Power. New Lessons from the French Experience", Ecoles de Mines, Paris, Dec. 2012.*

[b] *A. Grubler, "The Cost of the French Nuclear Scale-up: A Case of Negative Learning by Doing", Energy Policy 38 (2010).*

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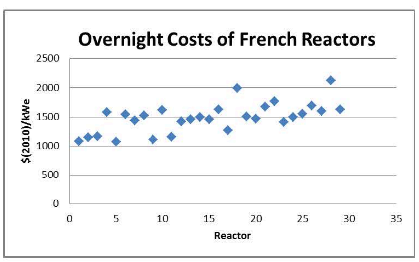
A case study: the French construction costs



Source of data: Cour des Comptes, 2012

	Plant	MW	Criticality	Type	Cost (E_{2010}/kW)	Cost ($/kW)
palier 900 MW	Fessenheim1.2	1780	1978	CP0	836	1087
	Bugey2.3	1840	1979	CP0	886	1152
	Bugey4.5	1800	1979	CP0	899	1169
	Damprierre1.2	1800	1980	CP1	1,217	1582
	Gravelines1.2	1840	1980	CP1	822	1069
	Tricastin1.2	1840	1980	CP1	1,188	1544
	Blayais1.2	1830	1982	CP1	1,110	1443
	Dampierre3.4	1800	1981	CP1	1,172	1524
	Gravelines3.4	1840	1981	CP1	856	1113
	Tricastin3.4	1840	1981	CP1	1,247	1621
	Blayais3.4	1820	1983	CP1	890	1157
	Gravelines5.6	1820	1985	CP1	1,093	1421
	SaintLaurent 1,2	1760	1983	CP2	1,120	1456
	Chinon 1,2	1740	1984	CP2	1,148	1492
	Cruas1.2	1760	1984	CP2	1,119	1455
	Cruas3.4	1760	1984	CP2	1,253	1629
	Chinon3.4	1760	1987	CP2	978	1271
palier 1300 MW	Paluel1.2	2580	1985	P4	1,531	1990
	Paluel3.4	2580	1986	P4	1,157	1504
	St Alban1.2	2600	1986	P4	1,129	1468
	Flamanville1.2	2580	1987	P4	1,287	1673
	Cattenom1.2	2565	1987	P'4	1,358	1765
	Belleville1.2	2620	1988	P'4	1,083	1408
	Cattenom3.4	2600	1991	P'4	1,149	1494
	Nogent1.2	2620	1988	P'4	1,194	1552
	Glofech1.2	2620	1992	P'4	1,305	1697
	Penly1.2	2660	1991	P'4	1,227	1595
palier 1450 MW	Chooz1.2	2910	2000	N4	1,635	2126
	Civaux1.2	2945	2002	N4	1,251	1626

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Regulatory stringency

- Expansion of the nuclear sector appears to be the best predictor of increased construction costs, as driven by increasing regulatory stringency:
  - *Example: AEC staff on the need for additional regulation for "Anticipated Transient Without Scram", in 1973:*
    "The present likelihood of a severe ATWS is acceptably small, in view of the limited number of plants now in operation. [...] As more plants are built, however, the overall chance of ATWS will increase, and the staff believe that design improvements are appropriate [...]".
- Common in every regulated sector: e.g. the current rapid increase in regulatory stringency for the oil-by-rail sector.
- In 1970 the publication of regulatory guidelines started (4 in 1970, 21 in 1971 and 33 in 1972, 143 in 1978 and 234 today for "division" 1, Power Reactors). 53 have since been withdrawn, and 10 have not been issued. Net of 171 today.
- For a given amount of power level, all the new requirements imposed during the '70s, approximately (Atomic Industrial Forum (now NEI), 1978):
  - *Doubled the amount of materials, equipment and labor;*
  - *Increased by two-thirds the amount of engineering effort.*

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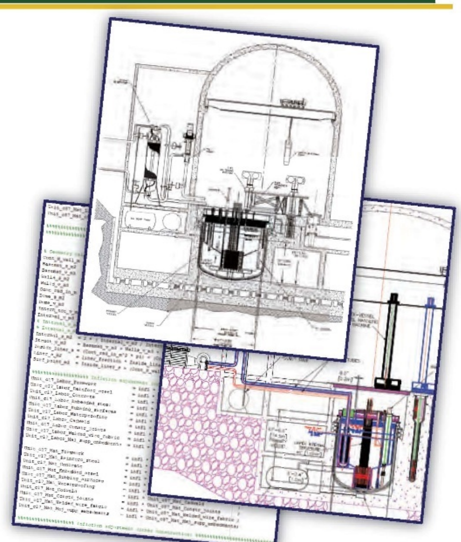
The Algorithm for the Capital Cost Estimation of Reactor Technologies (ACCERT)

- Functionality:
  - *Estimate the capital cost of advanced nuclear reactor designs.*
- Relevance:
  - *Facilitate independent assessments of claims about capital costs for advanced concepts.*
  - *Standardize approach for capital cost estimation.*
  - *Fills an identified gap in the tools available to DOE.*
  - *Perform preliminary cost assessments during the initial planning phase for new constructions.*
  - *Detailed cost models offer insight about the cost drivers for advanced designs.*
  - *This can be used to inform R&D decision making about cost reduction for advanced concepts.*



Report available at: https://publications.anl.gov/anlpubs/2018/07/144923.pdf

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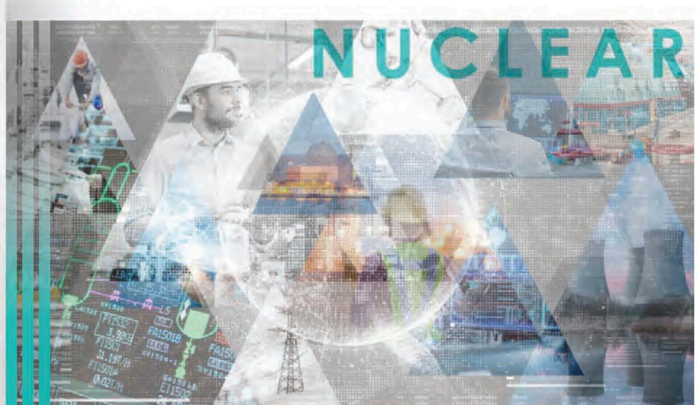
Exploring the Role of Advanced Nuclear in Future Energy Markets

Economic Drivers, Barriers, and Impacts in the United States

Andrew Sowder
Technical Executive

GAIN-EPRI-NEI Workshop on Economics-Based R&D for Nuclear Power Construction
January 17, 2019



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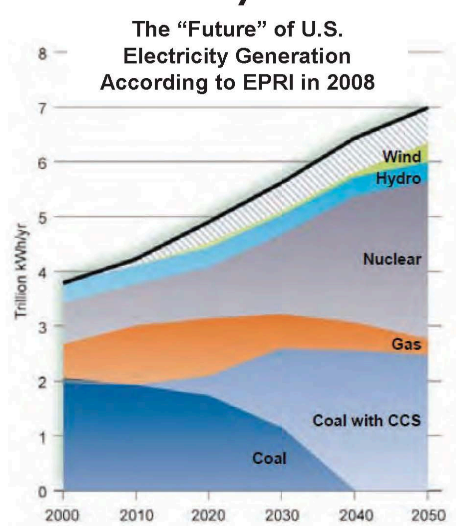
Global Context for Future of Nuclear: Uncertainty

- What will the price of natural gas be?
- What will the price of carbon be?
- What will the technology competition be?
  - Natural gas with CCS?
  - Renewables with grid-scale energy storage?
- "Unknown unknowns" … *i.e., the next shale gas revolution*



EPRI 2008. The Power to Reduce CO2 Emissions: The Full Portfolio.

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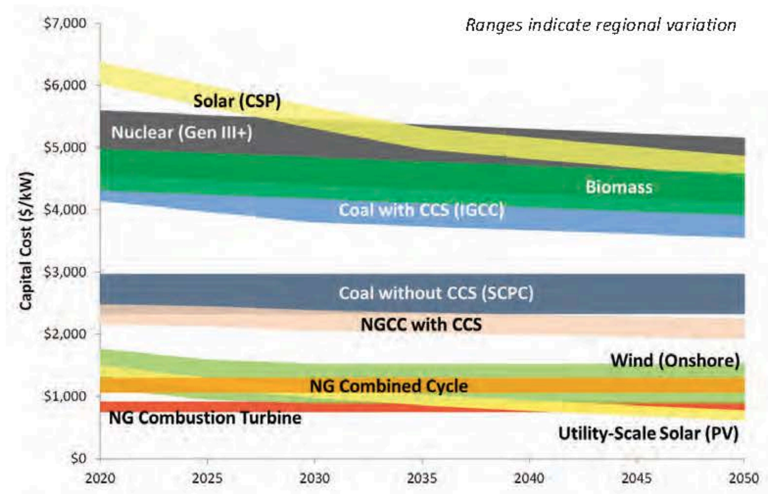
U.S. Cost Trajectories for Nuclear are NOT Compelling

EPRI REGEN Reference Case



Source: 2016 Integrated Generation Options Report (3002011806)

How can nuclear energy compete in future markets?

Analysis Approach and Scenario Matrix

Cost Scenarios

Value Scenarios	Market and Policy Sensitivities		Technology Sensitivities: Nuclear Capital Cost Scenarios ($/kW in 2030) $5,000	$4,000	$3,000	$2,000
Reference Natural Gas Prices	Electric Sector CO_2 Policy	$15/t-$CO_2$ Tax @ 5% 95% Cap				
	Additional Revenue Streams	$5/MWh $15/MWh				
	RPS with New Nuclear	50% by 2050, No Trading 50% by 2050, Trading				
High Natural Gas Prices						
Low Natural Gas Prices						

- Advanced nuclear capital cost sensitivities vary after 2030 ($/kW)
- Natural gas price trajectories based on EIA's *Annual Energy Outlook*
- Additional revenue streams → Proxy for PTC, sales of primary heat, or other products
- Expanded RPS: New nuclear considered an eligible resource; requirements expanded to all regions and stringency increased over time (30% by 2030 through 50% by 2050); sensitivity to national REC trading

US-REGEN: EPRI's In-House Electric Sector and Economy Model

- State-of-the-art computable general equilibrium (CGE) model of the U.S. economy with enhanced regional detail
- Includes detailed focus on the energy sector and electricity system
- Regional breakdown captures variability in generation mix, resources, and demand
- Tool to support scenario planning, IRPs
- Incorporates EPRI's proprietary datasets related to expected costs and performance of electric generation technologies and environmental controls
- Developed and maintained by EPRI staff

The New York Times — Business Day — Energy & Environment

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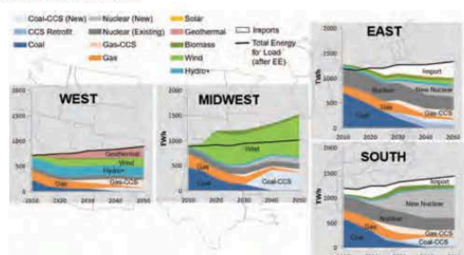
A New EPRI Computer Model Makes the Case for Regional Climate Solutions

By PETER BEHR of ClimateWire
Published: August 19, 2010

PRINT

The utility industry's top research group is making the case that regional solutions to the nation's climate policy challenges offer the best deal for consumers.



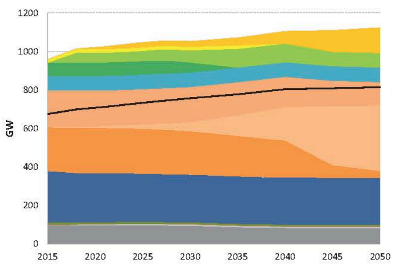
US-REGEN: EPRI's In-House Electric Sector and Economy Model

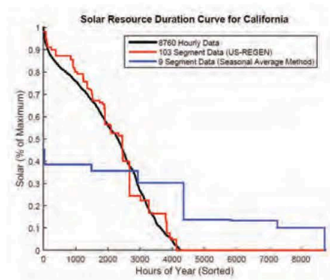
U.S. Regional Economy, GHG, and Energy

Capacity Expansion Economic Model, Long Horizon to 2050

Customizable State/Regional Resolution for Policy and Regulatory Analysis

Innovative Algorithm to Capture Wind, Solar, and Load Correlations in a Long-Horizon Model





For more information, see website at http://eea.epri.com

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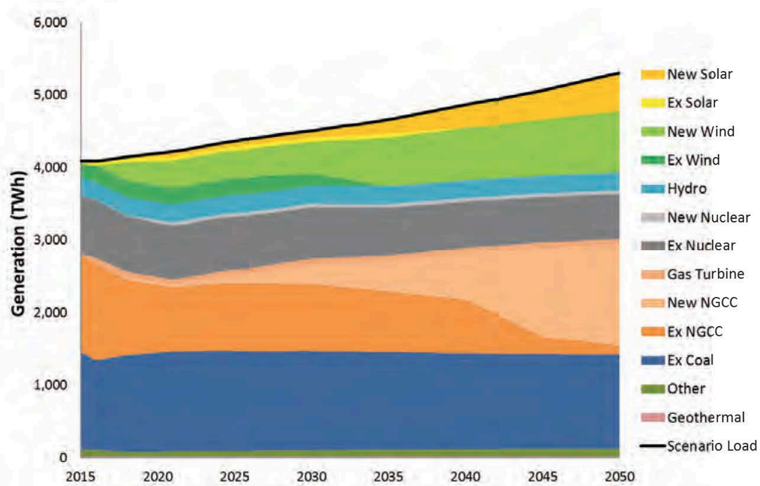
"The future ain't what it used to be." Yogi Bera

Absent Further CO_2 Policy with Reference Policies, Reference Gas Prices, and $5,000/kW Nuclear



- Absent additional policies, new builds are mostly gas, wind, and solar
- Existing nuclear and coal capacity remains unless gas prices are lower (80% of nuclear to 80 years)
- **New nuclear build limited to current projects**

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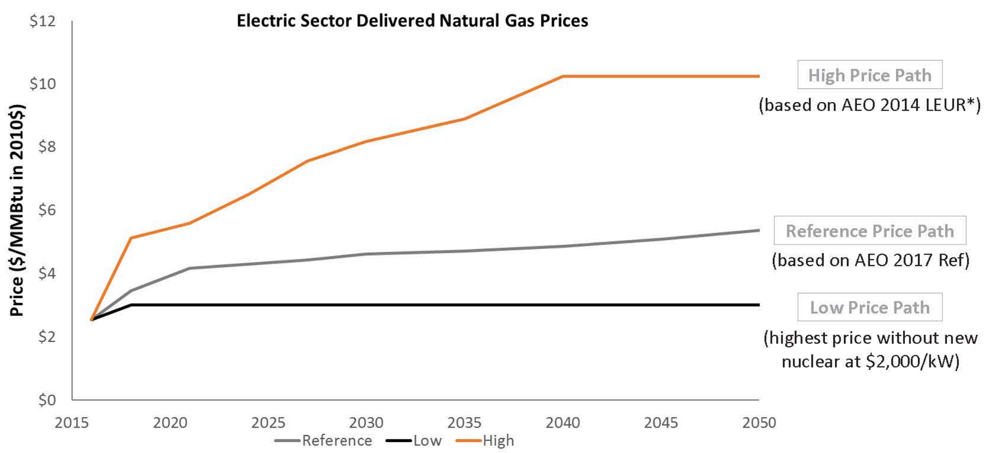
Natural Gas Price Uncertainty: Key Driver



*AEO = Energy Information Administration's Annual Energy Outlook; LEUR = low estimated ultimate recovery (i.e., high prices)

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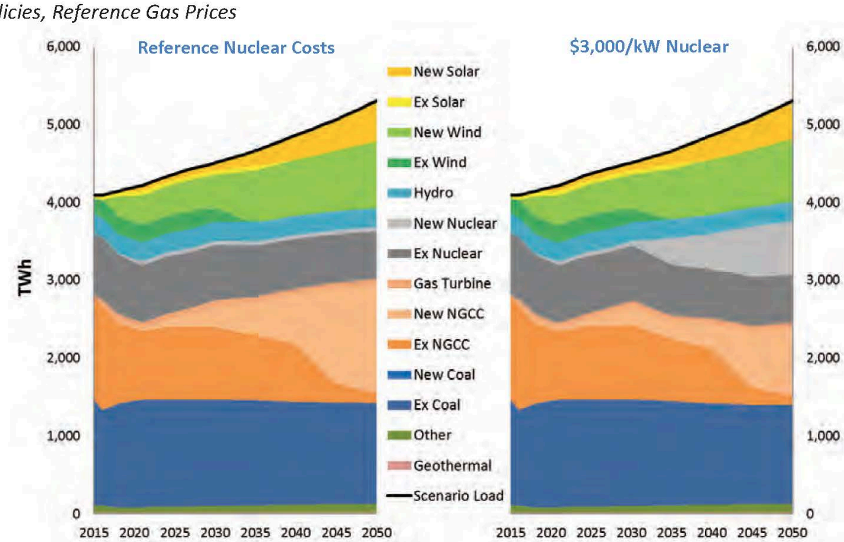
Lower Capital Costs Drive Expansion of Nuclear

Reference Policies, Reference Gas Prices



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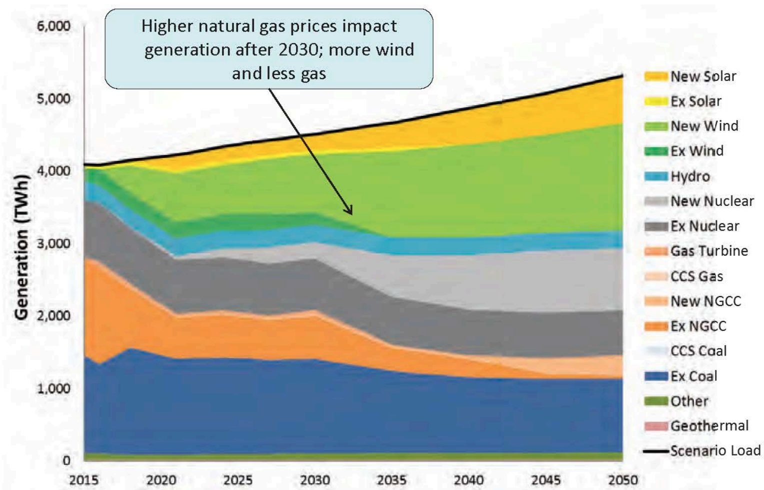
Higher Gas Prices Impact Investments and Dispatch

Reference Policies, High Gas Prices, $5,000/kW

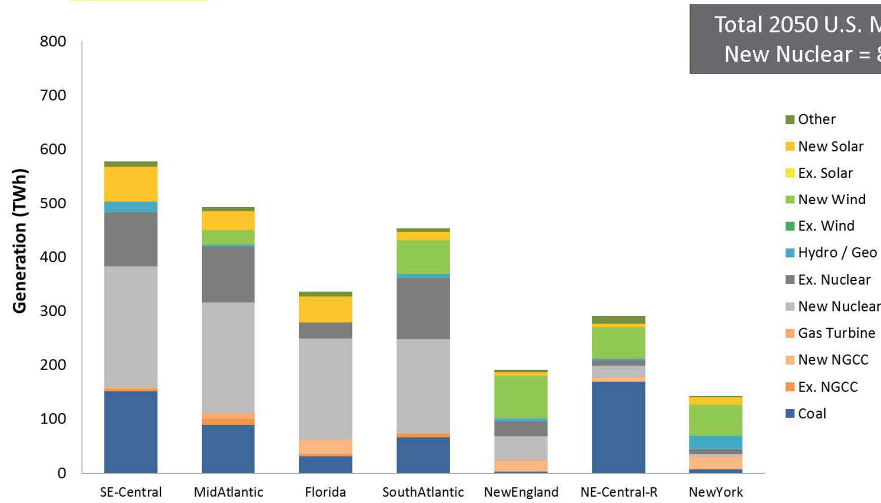


- New wind and solar are more competitive with high gas prices (even more than with lower renewables costs)
- **New nuclear is economic in some regions even without new policy**

Regional Effects: 2050 Generation with High Gas Prices

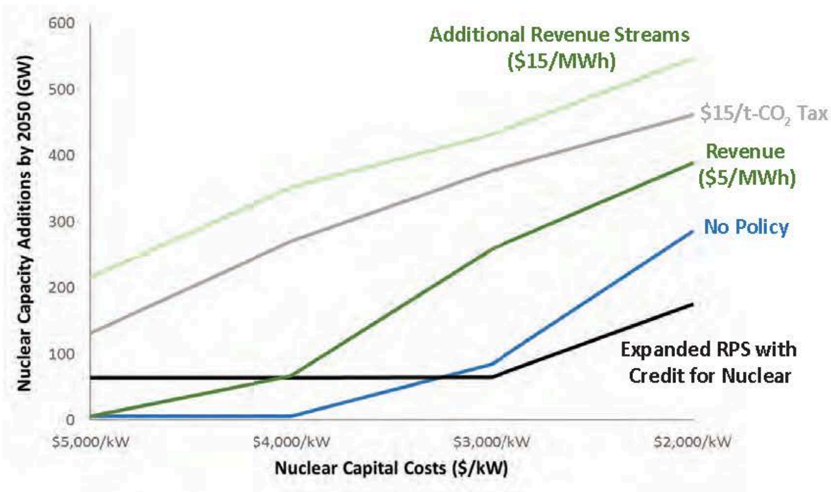
Reference Policies, High Gas Prices, $5,000/kW Nuclear Costs

Total 2050 U.S. Market for New Nuclear = 860 TWh



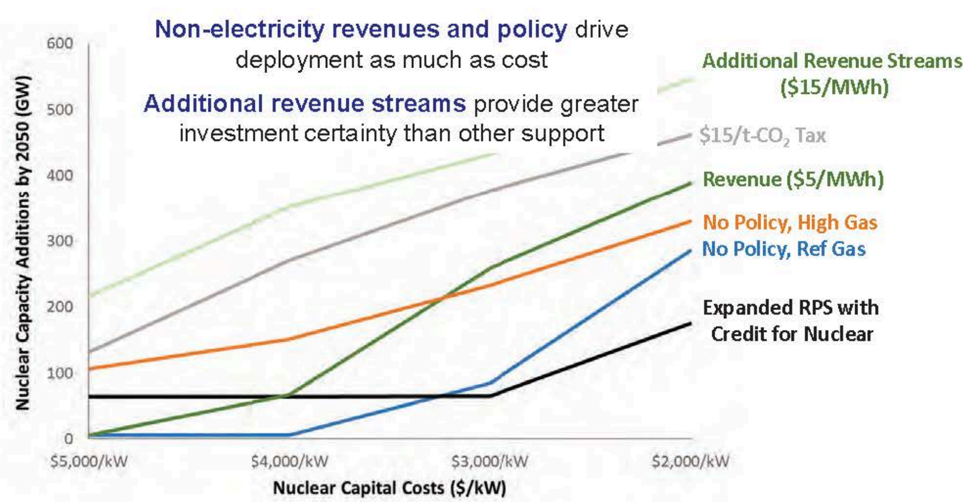
Big Picture: Advanced Nuclear Deployment vs. Cost

Reference Gas Prices



- Cost competitiveness of nuclear impacted by costs of other technologies and markets
- Without policy and with **reference gas prices**, levels below $4,000/kW are required for nuclear deployment
- With strong policy support, additions depend jointly on technology value and costs

Big Picture with Addition of High Gas Price Scenario



Key Drivers for Advanced Nuclear Role in Future Markets

- Competition (including arrival of disruptive technology)
- Capital costs
- Additional revenue
- Energy and environmental policies
- Regional factors and differences

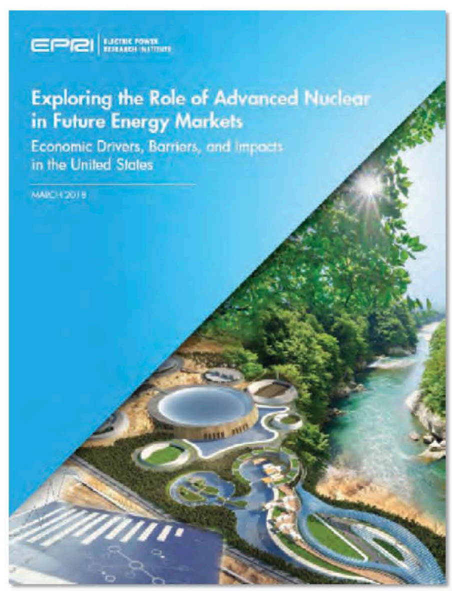
Future nuclear deployment is driven by multiple factors…not just cost.

Exploring the Role of Advanced Nuclear in Future Energy Markets:
Economic Drivers, Barriers, and Impacts in the United States

EPRI Report No. 3002011803

Published March 2018

https://www.epri.com/#/pages/product/3002011803/



Another recent study of potential relevance and interest:
Government and Industry Roles in the Research, Development, Demonstration, and Deployment of Commercial Nuclear Reactors: Historical Review and Analysis. December 2017. Report # 3002010478.
https://www.epri.com/#/pages/product/3002010478/

Additional References

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For more information, see our website at http://eea.epri.com

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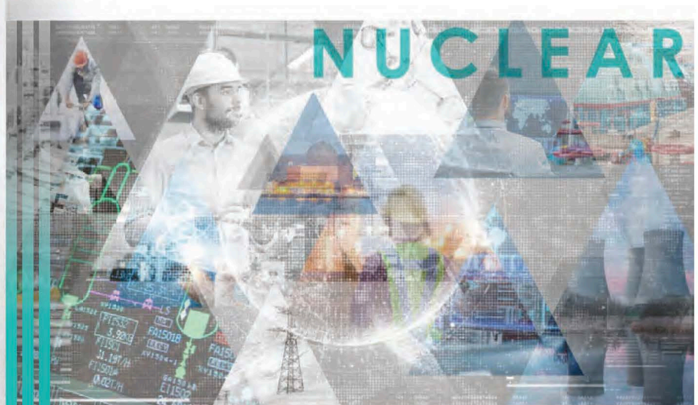

Economic-Based R&D Roadmap

Current Findings from EPRI's R&D Roadmap Development

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EPRI/GAIN/NEI Workshop
January 17-18, 2019
Washington, DC, USA

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Discussion Topics

- EPRI Perspective
- ANT Focus Areas
- Project Objective and Scope
- Goals for this Presentation/Workshop
  - Project summary and "expert elicitation"
- Evaluation Methodology
- Examples of Cost Drivers
- Opportunities
  - Direct and Indirect Cost Drivers
  - Project Planning
  - Project Execution
- Selected Examples
- Discussion

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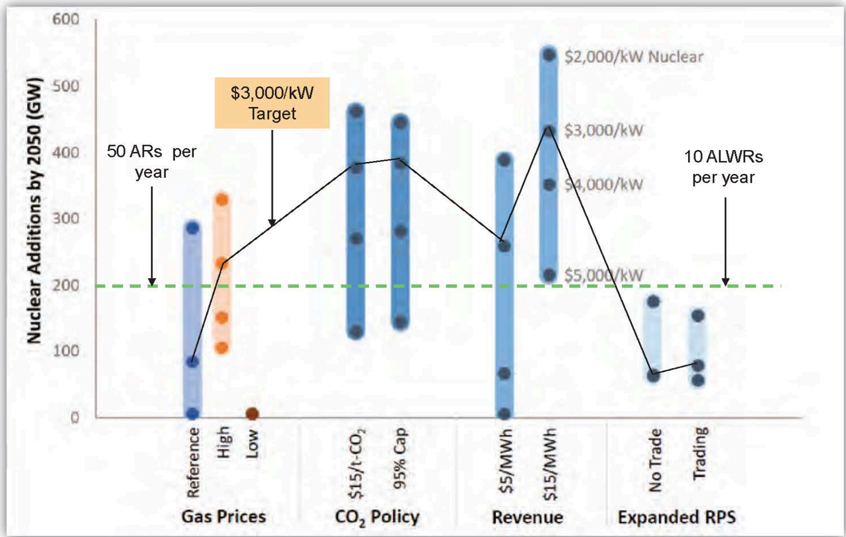
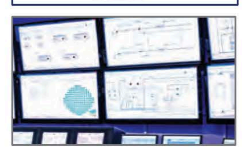
New Reactor Economics Study (3002011803)



ANT Technical Focus Areas

- **Engineering, Procurement, and Construction**
  - Siting, design, construction materials, and construction activities of the physical plant, including modular construction
- **Materials and Components**
  - Class 1, 2 & 3 piping systems and related components such as valves, heat exchangers, and pumps
  - Optimize methods for fabrication, installation, joining, inspection, and operations, including chemistry; and apply new applications of M&C
- **Modern Technology Application**
  - Maximize the use of existing, new, and possibly non-nuclear specific, technology in new nuclear plants
  - Gaps for the use of digital systems in new nuclear applications
- **Advance Reactor TI Program**
  - Strategic analysis and economics, technology assessment & tool development (ex. PHA-PRA), materials, owner-operator requirements



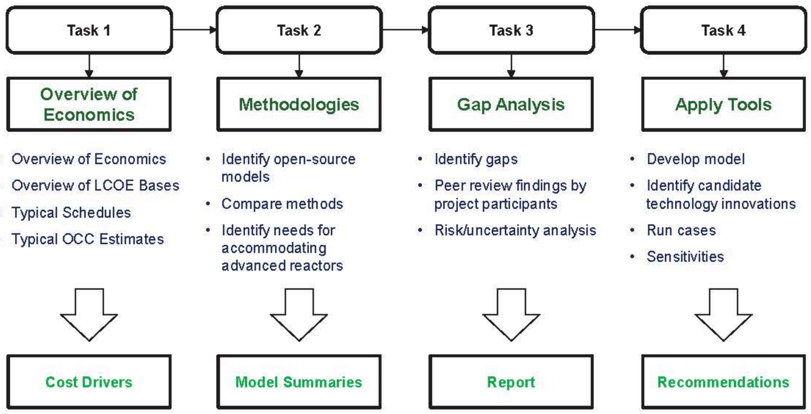
ANT Program Challenge Goal

- Prioritize EPRI (or other) R&D initiatives to help achieve
  - 30-50% reduction in cost of construction (>$2,500/kWe savings based on ~$5,500/kWe assumed baseline in this study to achieve $3,000/kWe construction cost)
  - Examples discussed herein are focused on 1GWe ALWR (for reasons discussed later)
  - Advanced reactor discussion tomorrow
- Supplement heuristics with economic modeling to establish such a prioritization
  - Use both historical and recent construction cost data and experience to assess opportunities
  - Quantify degree to which R&D successes could contribute to cost reductions
  - Consider both ALWRs and advanced reactors in such evaluations
- Timeframe
  - Realization in 5 to 10 years

Current Project Objective and Scope

- Objective
  - Predict the potential effect of new technologies, construction practices, or other research outcomes on nuclear power plant construction costs
  - Quantify effect in terms of overnight construction cost (OCC) reductions
  - Quantify effect of OCC reductions on cost of electricity
- Scope
  - Briefly summarize historical costs trends
    - 1970s to 1990's
    - Recent new builds in US and Europe
    - More recent overseas experience
  - Summarize methods used to estimate construction costs and cost of electricity
  - Pick an economic modeling approach
  - Use such a model to assess effects of specific initiative/practices
- Key project goal
  - Consider ALWRs and advanced designs

Task Overview



Important Perspective and Context

- Over the course of the next day's discussions, keep in mind….
  - There is a significant difference in experience in mature markets and new-build environments in terms of construction costs
    - <$3,000/kWe mature markets
    - >$5,500/kWe in new-build environments (or more)
- In discussing an R&D initiative or cost-driver, must distinguish between
  - What has been done in country X but not in country Y (but perhaps could…or could not apply to country Y)
  - What R&D initiatives have not been applied in X or Y but possibly could benefit both

These discussion should be open to talking about both types of "cost drivers" - country specific and non-country specific

Figures of Merit for the Evaluations

- **Overnight Construction Cost (OCC)** ← Main topic for this presentation
  - Direct costs + indirect costs = OCC
- Total Capital Investment Cost (TCIC)
  - OCC + escalation + interest during construction (IDC) + Owner's Costs
- Levelized Cost of Electricity (LCOE) (EIA Advanced Nuclear ~$90/MWh)
  - OCC ~40% (60% direct, 40% indirects) $5,500 ← Notional baseline
  - Owner's cost and contingency ~20% multiplier $1,110
  - IDC ~15-20% (or more) $1,000
  - Fuel~15%
  - O&M~15%
- Also, in this study, the level of detail in economic modeling…
  - Comparable to Class 4 or 5 Estimates using AACE terminology (study or feasibility phase)

Other Metrics (not specifically included in this study)

- O&M costs
- Fuel costs or benefits of accident tolerant fuel (ATF)
- Plant reliability (capacity factor)
- "Nuclear Promise"
- Non-base load operations (flexible operations)
- Siting (e.g., seismic isolation – part of separate EPRI project)
- Interaction with regulator or licensing approach (Part 50/52)

Why Use "Older" Construction Costs Estimate Methods?

- Construction cost and project scheduling models have been utilized in the power industry since the 1960's – not just for nuclear
- Audience/users:
  - Utilities, governments, regulators, research institutions, public sector, investors
- Results were/are used to support decision making:
  - (1) to build or not to build (nuclear or fossil, and now renewables and energy storage)
  - (2) timing
  - (3) plant type and size
  - (4) number of units, etc.
- Highlights/capabilities
  - 100's of man-years of effort invested in the design, validation, and population of these databases
  - Common framework used today in US and overseas

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Cost Modeling Review

- Approximately 20 models and ~100 associated references were reviewed
  - Models represent cost estimating methodologies from seven (7) countries
  - Range from detailed bottom-up estimates to top-down extrapolation of historical cost data
- 11 models downselected for comparison
  - Assumptions
  - Scope (Gen III, advanced reactors, etc.)
  - Approach
  - Source of data
- First expert elicitation workshop was held in June 2018
- Second elicitation (today and tomorrow)

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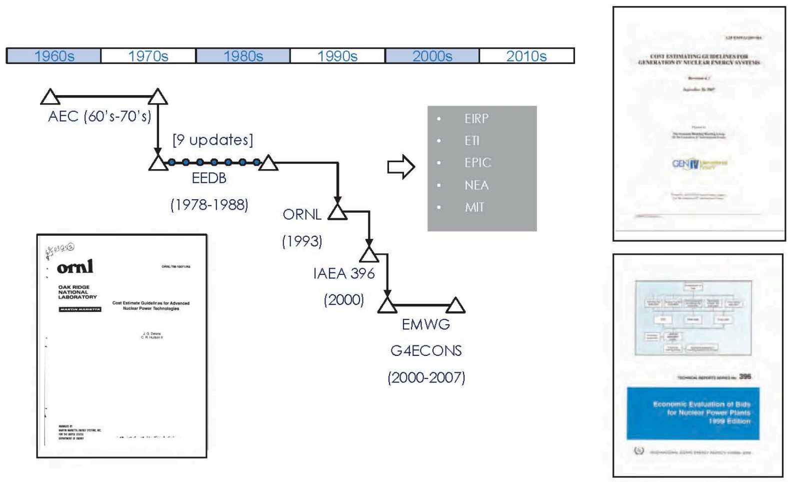
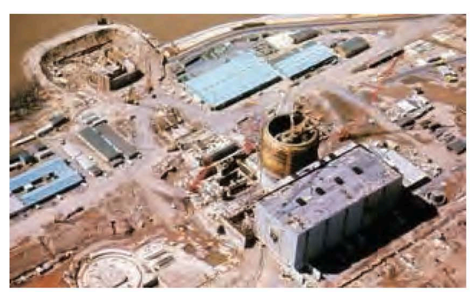
Notable Models Facilitating Assessment of Cost Drivers



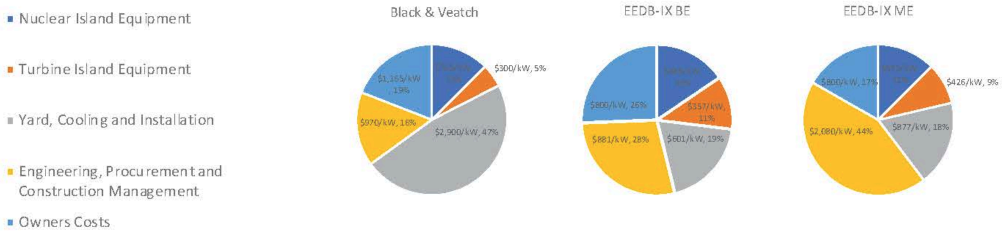
Historical Cost Drivers (1978-1987)

- Regulatory stringency and compliance
- Design changes
  - Equipment design changes
  - Material quantities and costs (37% above inflation)
- Commodity costs, equipment cost, required man-hrs
- Indirect costs (increased at rate 53% above inflation)
- Labor costs (increased at rates 44-220% above inflation depending on site)



TMI Under Construction circa 1970

Comparison of "Pie Charts"



EEDB Codes	Scope	B&V (2012)		EEDB IX-BE (2009 adjusted)		EEDB IX-ME (2009 adjusted)	
		Cost	Percent	Cost	Percent	Cost	Percent
22	Nuclear Island Equipment	$765/kW	13%	$485/kW	16%	$593/kW	12%
23	Turbine Island Equipment	$300/kW	5%	$357/kW	11%	$426/kW	9%
21, 24, 25, 26	Yard, Cooling and Installation	$2,900/kW	48%	$601/kW	19%	$877/kW	18%
91, 92, 93	Engineering, Procurement and Construction Management	$970/kW	16%	$881/kW	28%	$2,080/kW	44%
	Owners Costs	$1,165/kW	19%	$800/kW	26%	$800/kW	17%
	Total	$6,100/kW	100%	$3,124/kW	100%	$4,775/kW	100%

Note: Owners costs included

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EEDB (one open source model)

- Multi-year program to inform DOE
  - Began under AEC sponsorship in 1960s (NUS, 1969)
  - Total of 23 years of analysis
  - Nine phases or updates from 1978 to 1988
- 33 power plant configurations in total over 10 years
  - ~8 nuclear configurations
- Code-of Accounts System (up to 9-digit)
  - Assumed that all electric stations have same basic features at two to three digit level
- Direct Cost Accounts (linked to SDDs)
  - Commodities (concrete, rebar, piping, wiring)
  - Components
  - Equipment
  - Installation man-hours

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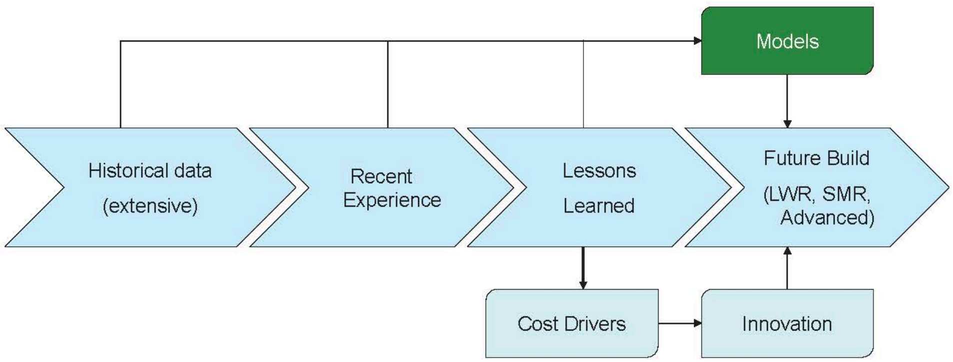
Approach for Technology Evaluation

- Assessment of the potential effect of R&D and associated innovative technologies on plant costs



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Example Assessment of an Advanced Technology

- Self Compacting Concrete (Champlin, 2018)
  - Flows more readily requiring less vibration after pouring
  - 20% increase in concrete materials cost, 34% decrease in concrete labor
- EEDB (DOE,1986) provides the total quantity materials used on site
  - Site materials are ~28% concrete, ~1% formwork, and ~69% rebar
- Chaplin provides an approximate cost breakdown for labor
  - Site labor cost is ~20% concrete, ~4% formwork, ~76% steel labor
- EEDB shows the breakdown of cost of structures in site labor, site materials, and factory equipment.
  - Site surface buildings (COA 21)
  - The turbine generator pedestal (COA 231)
  - Structures (COA 261)
- If self compacting concrete could provide the suggested savings to some or all concrete structures the resulting savings would be **~20-28 $/kWe or 1% of the target**

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High Level Roll up of COAs

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

EIRP

Direct Cost Accounts

EEDB (EMWG)	Category
21	Structures and Improvements
22	Reactor Plant Equipment
23	Turbine Plant Equipment
24	Electric Plant Equipment
25 (26)	Main Condenser/Heat Rejection System
26 (25)	Miscellaneous Plant Equipment
27	Special Materials
28	Simulators

Indirect Cost Accounts

EEDB (EMWG)	Category
91 (36)	Construction Services
92 (34)	Engineering Home Office Services
93 (37)	Field Supervision and Field Office Services

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EPRI Model for this Project

More Versatile for Identifying Cost Reduction Opportunities

	Conventional Code of Accounts (Gen IV Intl Forum/EEDB)	New Model
Includes detailed code of accounts for cost categories?	Yes	Yes
Includes build schedule and other time aspects?	No	Yes: Enables evaluation of innovations that compress schedule and reduce schedule overrun risk
Includes construction activities in sequence?	No	Yes: Aligns better with project planning process and simulates knock-on effects of delays early in project
Includes physical metrics underlying cost estimates?		
- Labor headcount	No	Yes: Shows labor needs for each activity and enables modeling of productivity improvements or labor innovations
- Labor wage rates	No: In DOE EEDB reports but not by COA	Yes: With flexible country data
- Labor man-hours	Yes: DOE EEDB has man-hours by COA	Yes: Labor headcounts x time for each activity
- Materials amounts and prices	No: In DOE EEDB reports but not by COA	Yes: Enables evaluation of innovations related to concrete and steel amounts and grades (nuclear vs. non-nuclear)
Includes modularization parameters and effects?	No	Yes: With default cost reduction estimates from GIF report
Includes risk?	No	Yes: Enables evaluation of innovations that mitigate cost or schedule risks

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Detailed Direct and Indirect Cost Worksheet

- Derived from EMWG COA with EEDB Data (PWR12)
- Screenshot below is 20 of ~400 inputs

Summary of Code of Accounts PWR12-BE EEDB Phase IX

Base Year 1987
Current Year 2018
ENR Cost Multiplier 2.50
Gross Mwe 1144

	Two-Digit Code of Accounts (COA)						Three-Digit Code of Accounts		Unit Cost per kWe				
Direct Costs	EEDB	IAEA	EMWG	Scope	Purpose	Examples	EMWG	Scope COA	Factory Equipment	Site Labor Hours (man-hrs)	Site Labor Cost	Site Materials	Total Cost
	20		10	Preconstruction Activities	Secure rights and permission to construct the plant	• Land and land rights	10	Total Cost	$/kW	MH/kW	$5/kW	$/kW	$6/kW
						• Site permits			$/kW	MH/kW	$5/kW	$/kW	$6/kW
						• Plant licensing			$/kW	MH/kW	$/kW	$/kW	$/kW
						• Plant permits			$/kW	MH/kW	$/kW	$/kW	$/kW
						• Plant studies			$/kW	MH/kW	$/kW	$/kW	$/kW
						• Plant reports			$/kW	MH/kW	$/kW	$/kW	$/kW
							TOTAL		$/kW	MH/kW	$5/kW	$/kW	$6/kW
	21	21	21	Structures and Improvements	House and support equipment, components, piping, ducting, wiring, fire protection, MEP, personnel, access, habitability structures	• On-Site Surface Buildings	21	Total Cost	$49/kW	5 MH/kW	$248/kW	$141/kW	$438/kW
						• Subsurface Foundations	211	Yardwork	$1/kW	1 MH/kW	$32/kW	$22/kW	$55/kW
						• Tunnels	212	Reactor Containment	$31/kW	1 MH/kW	$78/kW	$33/kW	$141/kW
						• Site Improvements	213	Turbine Bldg and Heater Bay	$1/kW	MH/kW	$24/kW	$25/kW	$51/kW
						Clearing	214	Security Bldgs	$/kW	MH/kW	$2/kW	$1/kW	$3/kW
						Excavation	215	Prim Aux Bldg and Tunnels	$7/kW	MH/kW	$23/kW	$10/kW	$40/kW
						Grading	216	Waste Processing Building	$1/kW	MH/kW	$20/kW	$10/kW	$31/kW
						Roadways	217	Fuel Storage Building	$2/kW	MH/kW	$10/kW	$10/kW	$22/kW
						Rail Spurs	218A	Control Room/DG Bldg	$3/kW	MH/kW	$24/kW	$12/kW	$39/kW
						• Buildout/detailing	218B	Admin and Service Bldg	$2/kW	MH/kW	$7/kW	$5/kW	$15/kW
						• Does not include	218D	Fire Pump House	$/kW	MH/kW	$1/kW	$/kW	$1/kW
						Equipment Pedestals	218E	Emergency Feed Pump Bldg	$/kW	MH/kW	$4/kW	$2/kW	$5/kW
						Heat Reject Bldg	218F	Manway Tunnels (RCA)	$/kW	MH/kW	$1/kW	$/kW	$2/kW
							218G	Electrical Tunnels	$/kW	MH/kW	$/kW	$/kW	$/kW
							218H	Non-Essential Switchgear	$/kW	MH/kW	$1/kW	$/kW	$1/kW
							218J	Main Steam and FE Chases	$/kW	MH/kW	$12/kW	$6/kW	$17/kW
							218K	Pipe Tunnels	$/kW	MH/kW	$/kW	$/kW	$1/kW
							218L	Tech Support Center	$/kW	MH/kW	$1/kW	$1/kW	$2/kW
							218P	Equipment Hatch Missile Shield	$/kW	MH/kW	$/kW	$/kW	$/kW
							218S	Wastewater Treatment	$/kW	MH/kW	$1/kW	$1/kW	$2/kW
							218T	UHS Structure	$/kW	MH/kW	$7/kW	$3/kW	$10/kW
							218V	MCR Air Intake Structure	$/kW	MH/kW	$/kW	$/kW	$/kW

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Cost Drivers Discussions

Direct Costs
- Materials and commodity costs
- Capital equipment costs
- Labor rates
- Workforce siting costs (per diems, etc.)
- Productivity

Indirect Costs
- Home office engineering costs
- Construction management and staff cost/size
- Indirect labor rates
- Workforce siting costs (per diems, etc.)

Project Preparation
- Design completion and Standardization
- Pre-construction rigorous integrated schedule
- Design for constructability
- Avoiding overdesign
- Use of project planning software tools

Project Implementation & Execution
- Managing change (engineering)
- Supply chain
- Non-domestic supply chain management
- Implementation of best construction practices
- Regulatory learning curves
- Change management
- Non-optimal construction practices

Technical Issues
- Design tolerances
- Backfill requirements
- Rebar placement
- Optimum use of modularization
- Transportation associated with modularization

Realization of Advanced Tech and Practices
- Modularization
- Construction practices

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Example Opportunities

Opportunities

- Best construction practices
- Modularization
- Steel plate construction
- Advanced concrete
- Excavation/embedment technology
- Seismic isolation
- High performance materials
- Additive manufacturing
- Innovative external event shielding
- HYS rebar (or alternative rebar)
- Advanced concrete construction
- Effective implementation of digital I&C
- Advanced controls
- Data management and analytics
- Mobile and wearable devices
- Robotics
- Improved NDE for construction
- Safety class/safety boundary reclassification
- Commercial grade dedication streamlining
- Worker productivity tools
- Methods for improving/assuring NOAK benefits
- Advanced sensors for operations (reducing LCOE)

Context of Today's Cost-Driver Discussions

- NOAK ALWR plant assumed (discussion of NOAK/FOAK, learning curves later)
- Wide range of baselines from which to choose….
  - Mature standardized design market with established supply chain and order book
    - $2,500/kWe
  - Black & Veatch Study
    - $6,100/kWe
  - EEDB PWR12-BE adjusted to 2017
    - $5,500/kWe
  - EEDB PWR12-ME adjusted to 2017
    - >$10,000/kWe
  - ….others
- For this review, baseline OCC is $5500/kWe with target reduction to $3000/kWe
- Therefore, we are "looking for" $2500/kWe in this scenario (45% reduction)
  - Reduce "the bill" by this amount

Another Qualifier….

- Since we are looking at OCC and not LCOE in this presentation, schedule affects outcome here only to the extent it affects directs and indirects
  - Example: increased productivity which results in shorter schedule and therefore reduces direct labor costs and indirect costs
- Schedule will of course have major effect on final costs (LCOE, TCIC) due to interest during construction, financing models, regulatory environment, accounting rules, etc.
- Interest cost reductions could be comparable to the target reductions in OCC

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Six Opportunity Categories

- 1. Direct Costs
- 2. Indirect Costs
- 3. Project Preparation
- 4. Project Implementation/Execution
- 5. Technical Issues
- 6. Realization of Advanced Technologies and Practices

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1. Direct Cost Opportunity

- Opportunity (COAs 21-26) : $3500/kWe "bill"
  - 64% of OCC
  - Other studies site from 36 to 71% of OCC
- Why is this an opportunity?
  - Commodities and equipment costs increased 37% above inflation in period from 1979 to 1989 (DOE, 1988)
  - More recently, equipment costs increases averaged 11% per annum (Rothwell, 2016)
  - Commodities up by $500/kWe from 2007 to 2011 (Univ Chicago - EPIC, 2011)
  - Labor cost portion of directs (about 30-40% of OCC) represent up to $1,500/kWe opportunity
    - Consisting of wage rates, OH, G&A, profit, productivity, and work schedules
  - In Japan, in absence of inflation, labor cost effect on OCC rose 50% over period from 1996 to 2016
- How can we realize?
  - Reduce factory equipment costs (currently baselined at about $1000/kWe)
  - Standardization
  - Mature NQA and commercial parts supply chains
  - Redefine the safety/non safety boundary (although out of scope for today's discussion)
  - Increased productivity installation/construction
  - Realization of advanced construction practices
  - Modularization (for ALWRs, SMRS, and Advanced Designs)

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2. Indirect Cost Opportunity

- Opportunity (COAs 91-93) : $2000/kWe "bill"
  - 36% of OCC (in this analysis)
  - Other studies site from 10 to >60% of OCC
  - Indirect Costs
    - Construction Services
    - Engineering and Home Office
    - Field Supervision and Field Office Support
- Why is this an opportunity?
  - Early nuclear deployment expectation was indirect costs would be only 10-30% of OCC
    - Particularly in a utility led build at non FOAK sites
  - Later EEDB evaluations estimated in excess of 50% of OCC at some plants (DOE, 1988)
  - Latest estimates (Ganda, 2018) up to 60% multiplier on directs or ~40% of OCC
  - In EPC contract approach, could be higher?
- How can we realize?
  - Design and build model (EPC, utility lead, AE with utility lead?)
  - Finalization of design (see next slide)

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3. Project Preparation Opportunity

- Opportunity (effect on COAs 20s and 90s): $1000/kWe "bill" due to inadequate project preparation
  - Estimated effect of *design not being final*
    - 25% due to engineering and other labor (2 million man-hrs)
    - 25% due to material and equipment changes (estimate 25% bump in equipment cost)
    - 50% due to 2 year schedule increase (not IDC, but carrying indirects) (GIF, 2007)
  - 60% of difference between EEDB PWR12-ME and PWR12-BE
- Why is this an opportunity?
  - Plants have been built using essentially complete designs
  - Schedule improvements have been achieved at N-pack sites
    - Shin Kori 1: 72 months (OPR-1000)
    - Shin Kori 2: 64 months (OPR-1000)
    - Shin Kori 3: 54 months (APR-1400)
    - Shin Kori 4: 54 months (APR-1400)
- How can we realize this opportunity?
  - Multiple project needs ("85%" design finalization, experienced project management, supply chain, etc.)
  - Standardization? – perhaps with SMRs and Advanced Reactors leading this opportunity
  - Modularization

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4. Project Implementation/Execution Opportunities

- Opportunity (affects direct and indirect labor costs): ~$1200/kWe "bill" (total labor)
  - Two example opportunities in implementation/execution
    - Schedule (and scheduling)
    - Productivity
  - Baseline schedule of 72 months (median from 1970 to 1995 was 80 months; 1996 to 2014 median 83 months)
    - Decreasing to 60 months decreases indirects about $230/kWe
    - This is in addition to saving in IDC
  - Productivity (based on ~12 Million MH/unit)
    - US baseline (reference) — $0/kWe (baseline)
    - "Best experience" overseas — $475/kWe lower cost
    - 20% improvement in best experience — $600/kWe lower cost (50% savings theoretically)
- Why is this an opportunity?
  - Has been done in multiple regions and markets
- How can we realize this opportunity?
  - Training and tools (integrated schedules)
  - Realization of NOAK, N-pack and learning curve benefits
  - Reverse the "unlearning" trends of US builds in 1980's

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Construction Practices


Kashiwazaki Kariwa-7 Supermodule


SP Reinforced Concrete


Automatic/HYS Welds


Open Top


Heavy Lift


Design

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5. Technical Issues – Some Examples

- Opportunity (affects direct and indirect costs): Site specific
  - Perhaps $0/kWe to $200/kWe for a cumulative two year delay due to technical issues
  - In addition to IDC cost increase which would likely be much higher
- Why is this an opportunity?
  - It may be from an R&D perspective if generic technical issues identified
    - Siting could be one
  - May be most valuable as an opportunity for non-LWR advanced designs
    - Materials
    - Corrosion
    - NDE
    - Codes and standards support
    - Licensing support
- How can we realize this opportunity?
  - Identify gaps in non-LWR technologies that may be resolved with R&D

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6. Realization of Advanced Technologies and Practices

- Opportunity (affects direct and indirect costs): $850/kWe
  - 15% of costs (NEA, 2000)
  - Significant (IAEA, 2011)
  - Numerous other citations
- Why is this an opportunity?
  - Benefits of implementation of advanced technologies and construction practices have been realized but probably above those assumed in PWR12-BE (the $5,500 baseline)
  - Example
    - Modularization benefit in ALWR may be only 1-4% (NEA, 2000) – but that could be significant in reduction of overall projects risk, enhanced quality, etc. (see Kang, IAEA, 2014)
    - Other studies for SMRs suggest >40% reduction (Moronati, 2018; Champlin 2018)
- How can we realize this opportunity?
  - Country specific
  - Design specific

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Example Savings for Five Cost Driver Opportunities

OCC	$5,500/kW
Schedule	72 months
Target Reduction	$2,500/kW

Number	Candidate Cost Driver	Total Cost/Impact (and therefore potential)	Target Reduction	Net Reduction in OCC (example)	Percent Goal	Cumulative Reduction
		OCC Baseline				
1	Direct Costs	$3,500/kW	15% reduction factory equipment $ 5% reduction in installation costs (example: modularization)	$220/kW	9%	9%
2	Indirect Costs	$2,000/kW	Reduce to 30% of OCC plus shortened schedule (60 months) (From 36%)	$530/kW	21%	30%
		Opportunity				
3	Project Preparation (Design Maturity)	$1,000/kW	50% reduction in impact of incomplete design	$500/kW	20%	50%
4	Project Execution (Project Labor)	$1,200/kW	Reduce schedule to 60 mos. Increase productivity 30%	$430/kW	17%	67%
5	Advanced Technologies	TBD	Reduce OCC by 5%	$275/kW	11%	78%

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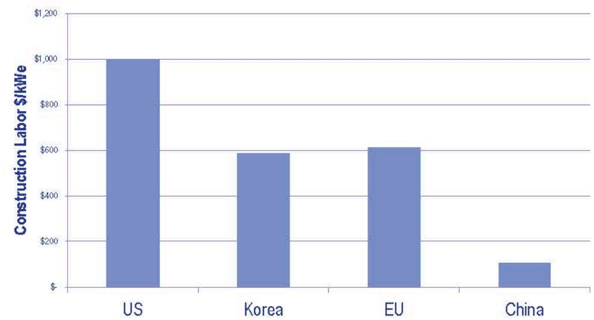
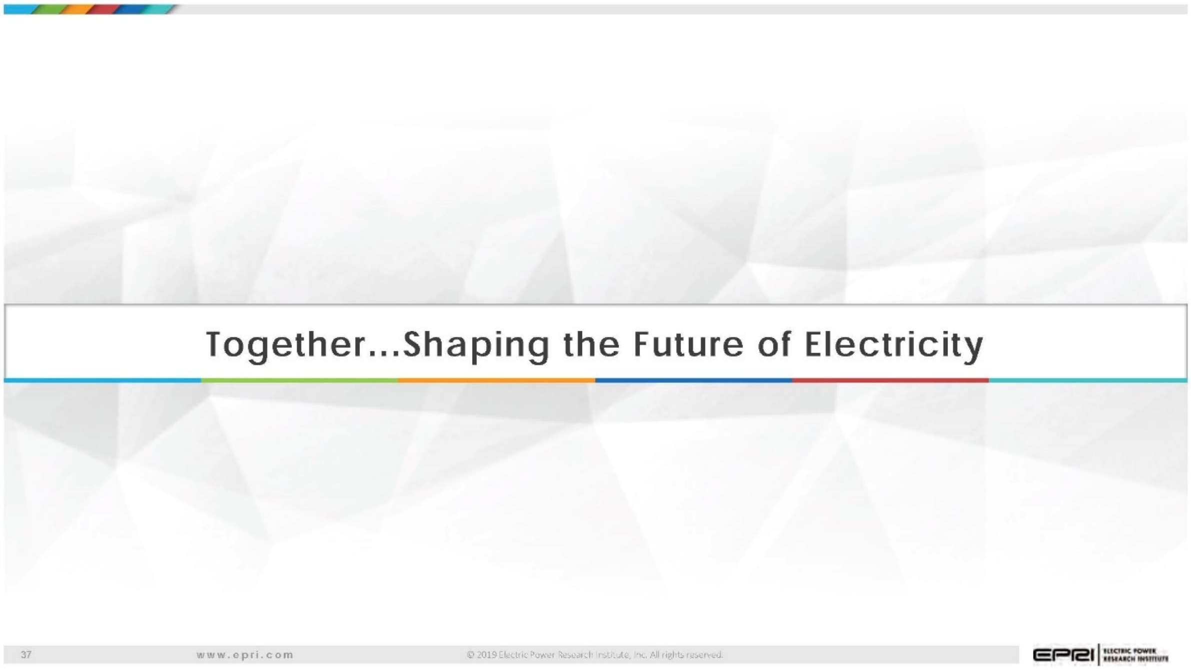
More Caveats….

- Remember the $5,500/kWe baseline already assumes utilization/benefits of advanced construction practices such as modularization
  - Extrapolated from EEDB PWR12-BE (about 4% above inflation from 1988 to 2017)
  - So 5% benefit of advanced technologies in previous slide is above and beyond this baseline
- Direct and Indirect costs are 15-35 % labor so this is very country specific



Wrap-Up

- EPRI Project is attempting to define benefits of R&D initiatives
- Target “goal” is 45% reduction in OCC
  - But incremental and cumulative progress should not be ignored
- So far, it is challenging in Western markets to predict achieving more than about 40% of goal with targeted reductions in direct and indirect costs for a given design/schedule
- Better opportunities may exist in project planning (e.g., design completion) and execution
- Another difficult question – can what is being achieved in country “X” be achieved in country “Y” in the next 5-10 years?
  - Supporting progress toward targets for new deployment by 2050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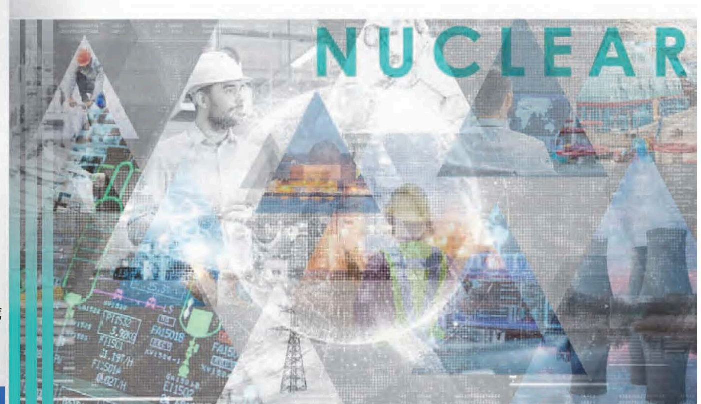
Workshop about Economics-Based R&D for Nuclear Power Construction

Open Discussion and Ideation

David B. Scott
Sr. Technical Leader, ANT

Chuck Marks
Dominion Engineering

January 17-18, 2019



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Revision Date: 2018-01-04

Agenda (Morning / Afternoon)

Workshop about Economics-Based R&D for Nuclear Power Construction

Morning Session, January 17, 2019

Time	Topic	Lead
8:00 am	Registration and Breakfast	
8:30 am	**1. Welcome and Introduction** Review of ANT Program; Workshop overview and purpose	D. Scott, EPRI
9:00 am	**2. Economic Perspective – US** New reactor cost reduction	M. Nichol, NEI
9:30 am	**3. MIT Study on Nuclear Power Cost** The future of nuclear energy in a carbon-constrained world	E. Ingersoll, Lucid Catalyst
10:00 am	Break	
10:30 am	**4. Economic Perspective – UK** ETI Nuclear cost drivers project	E. Ingersoll, Lucid Catalyst
11:00 am	**5. Analysis of US Historical Capital Costs** The historical construction cost and cost drivers of nuclear power plants	F. Ganda, Argonne National Laboratories
11:30 am	**6. Economic drivers, barriers, and impacts in the US** Exploring role of advanced nuclear in future energy markets	A. Sowder, EPRI
12:00 pm	Lunch	

Workshop about Economics-Based R&D for Nuclear Power Construction

Afternoon Session, January 17, 2019

Time	Topic	Lead
1:00 pm	**7. Economic Based R&D Roadmap** Current findings from EPRI's R&D roadmap development	C. Marks, DEI
2:00 pm	**8. Open Discussion – Cost Driver Category #1** Participant input on current findings from the R&D roadmap development	Led by EPRI / DEI (attendee participation)
2:30 pm	**9. Open Discussion – Cost Driver Category #2** Participant input on current findings from the R&D roadmap development	Led by EPRI / DEI (attendee participation)
3:00 pm	Break	
3:30 pm	**10. Open Discussion – Cost Driver Category #3** Participant input on current findings from the R&D roadmap development	Led by EPRI / DEI (attendee participation)
4:00 pm	**11. Open Discussion – Cost Driver Category #4** Participant input on current findings from the R&D roadmap development	Led by EPRI / DEI (attendee participation)
4:30 pm	Adjourn	

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Agenda (Morning)

Workshop about Economics-Based R&D for Nuclear Power Construction

Morning Session, January 18, 2019		
Time	Topic	Lead
8:00 am	Breakfast	
8:25 am	12. Recap	D. Scott, EPRI
8:30 am	13. Open Discussion – Cost Driver Category #5 Participant input on current findings from the R&D roadmap development	Led by EPRI / DEI (attendee participation)
9:00 am	14. Open Discussion – Cost Driver Category #6 Participant input on current findings from the R&D roadmap development	Led by EPRI / DEI (attendee participation)
9:30 am	15. Roadmap Development for R&D Participant input on R&D multiyear plan	Led by EPRI / DEI (attendee participation)
10:00 am	Break	
10:30 am	16. Roadmap Development for R&D (continued) Participant input on R&D multiyear plan	Led by EPRI / DEI (attendee participation)
11:30 am	17. Advanced Reactor (AR) Construction Application of R&D roadmap and additional AR needs	Led by EPRI / DEI (attendee participation)
12:00 am	Lunch and Adjourn	

Cost Drivers (Ideas for solutions are in green)

- Design Optimization / Designing for Constructability (Need to be inexpensive and swift)
  - Design for cost minimization, constructability, maintainability, operability, inspection-ability (create a functional design)
  - Design change without affecting licensing basis
  - Increase the use of BIM to support design optimization
  - Increase the use of AI for bottom's up design
  - Design away accidents to eliminate components and decrease volume of materials
- Regulatory Requirements / Conservatisms Stack-ups / Design Requirements
  - Separate non-nuclear from license (e.g., turbine island)
  - Remove unnecessary conservatism by NRC (e.g., digital I&C, source term/LNT, seismic conservatism stack-up)
  - Rapid NRC decision/issue resolution
- Designing Around Civil / Structural
  - Determine the best use of modules (study accelerated bridge construction)
  - Increase appropriate use of factory fabrication
  - Increase appropriate use of steel-plate composites
  - Increase appropriate use of ultra high performing concrete and metals (including high strength reinforcement)
  - Increase appropriate use of seismic isolation

Cost Drivers (Ideas for solutions are in green) (continued)

- Inspection (QA/QC) Delays
  - Automate the inspection and qualification of concrete
  - Develop continual or near-real-time inspections of material and member placement (deployment can be through laser, drone, scanner, etc.)
  - Automate the development of as-built drawings / conditions
  - Increase appropriate use of sensors (including for concrete placement)
  - Increase appropriate use of automated monitoring/control
  - Increase appropriate use of advanced NDE (e.g., GPR, UT, other)
  - Develop rationale for fewer inspections
- Variations in Materials
  - High performance materials
  - Increase appropriate use of advanced manufacturing and welding
  - Develop smart formwork for concrete
  - Develop smart batch plant for concrete
  - Develop method to testing concrete prior to loading in truck

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Cost Drivers (Ideas for solutions are in green) (continued)

- Incentivizing Stakeholders
  - If appropriate, increase small demos for vendor and supply chain
- Worker Productivity
  - Increase appropriate use of artificial intelligence (AI) and machine learning
  - Increase appropriate use of augmented reality
  - Incentivize personalized productivity
  - Address “swarm”
  - Improve training/qualification
  - Develop ways to automate construction
  - Link the use of a smart batch plant with in-situ work activities
- Paperwork Slowness / Alternatives
  - Digitize work packages
- Workforce Training (qualifications) – may be overlap with worker productivity
  - Inspector training (increased expertise)

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Cost Drivers (Ideas for solutions are in green) (continued)

- Excessive Margin (risk-informed, performance based); (see Conservatisms Stack-up on slide 4)
  - RTNSS and move to 3 classes of safety (internationally accepted)
- Unknown Risks
  - Increase appropriate use of rapid prototyping (see military examples of use)
  - Increase appropriate use of BIM / modeling
  - Develop process / design change orders without impacting schedule
  - Address safeguards and security
  - Develop process for go/no-go components
  - Demos
- Supply chain / Specialized / Unique components / Difficulty with CGD process (Construction and Manufacturing groups are unable to buy off-the-shelf)
  - Utilize pre-existing supply chain
  - Reduce the amount of Q components, expand use of commercial grade dedication
  - Reduce barriers-of-entry for suppliers
- Non-severability of Design Features

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Cost Drivers (Ideas for solutions are in green) (continued)

- Code Committee Slowness
  - Risk-informed guidance on use of code in-lieu of rulemaking
  - Incentivize resources (volunteer) to develop standards
  - Increase collaboration among multiple code committees
  - Improve pathway for NRC (or other regulator) acceptance without waiting for code case

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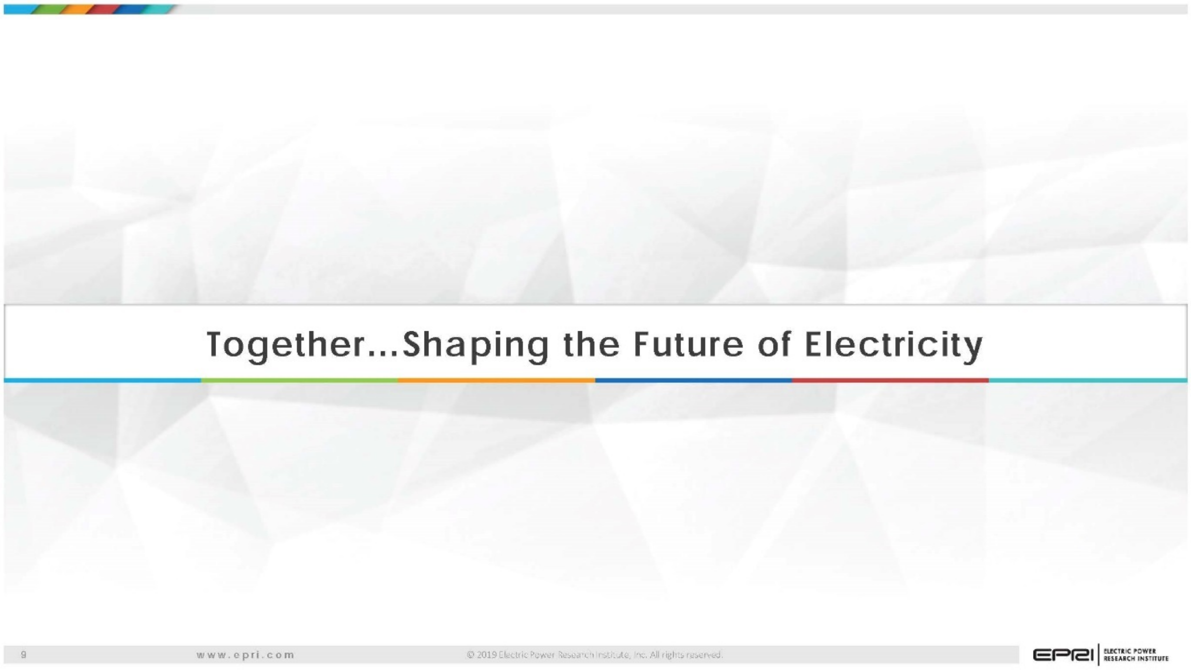
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ADVANCED NUCLEAR TECHNOLOGY (ANT) PROGRAM EPRI ANT ECONOMIC-BASED R&D FOR NEW NUCLEAR CONSTRUCTION WORKSHOP 1

Together...Shaping the Future of Electricity

Economic Based R&D

Review of Historical NPP Capital Cost Estimating Methodologies
Task Status Report

Dominion Engineering, Inc.

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Presented to:
EPRI
Charlotte, NC

Presented by:
Bob Varrin
Velvet Moroney
Dominion Engineering, Inc.

June 14, 2018

Outline

- Overview
- Brief summary of individual project tasks
- Update on evaluation of existing cost models for new nuclear
- Status on modeling effort
  - Overnight construction cost (OCC) model
  - Materials and commodities model
  - Labor cost model
- Work in progress
- Open discussion (elicitation) on potential impact of innovative technologies on new build

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Overview

- Cost estimating models have been utilized in the power industry since the 1960s
  - Results have driven a wide range of decisions ranging from decision to build, timing, plant size, number of units, etc.
- Audience/users
  - Utilities, governments, research institutions, public sector, investors
- However, cost studies (particularly early stage) have historically been inaccurate in predicting final cost and schedule for nuclear
  - Not necessarily a situation that is unique to nuclear
  - Particularly relevant over past decade in countries without active design and build programs
- Uncertainties in build schedules in Western countries
  - Design changes, regulation, supply chain challenges, low productivity

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Overview (continued)

- Despite past experience, models can still provide an opportunity for quantitative assessment of the potential impact of innovative technologies on cost of construction
- Modeling goals
  - Characterize and confirm existing conclusions regarding cost drivers
  - Use model to evaluate the impact of specific technologies
  - Identify risks and uncertainties
  - Assess timeline for need, qualification and deployment
  - Carefully implemented, models can be effective tools for quantitatively evaluating cost-benefit of emerging technologies or adaptation of lessons learned from other industries (overnight cost and LCOE)
- Key feature – Improve granularity of existing cost predictions

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Scope

- Summary
  - LWRs (GenIII/III+) - focus
  - SMRs (subject to availability of inputs)
  - Advanced reactors (examples to the extent data is available)
  - Identification of and sensitivity of cost drivers
  - Address regional or national variables (e.g. labor costs)
  - Consider business models (SOEs versus public utilities versus private sector)
- Timeframe
  - 5 to 10+ year window
- Uncertainties/confidence bands ("Producer-Consumer Risk")
  - Deterministic "sensitivity" cases rather than full probabilistic at this time
- Direct and Indirect Costs
  - No Owner's Costs, contingency, IDC, or Allowance for Funds Used during Construction (AFUDC)

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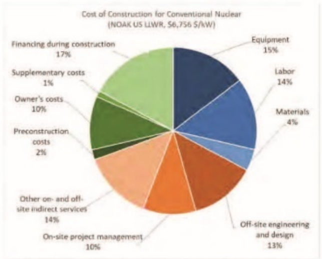
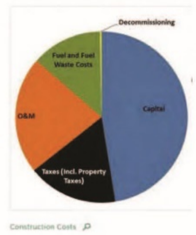
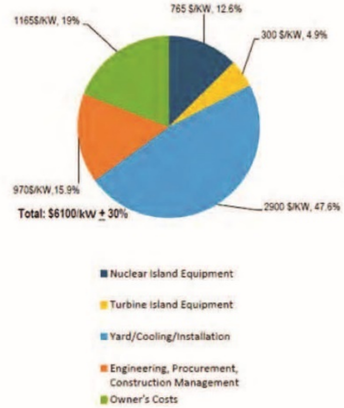
Examples of Cost Estimate Reporting



Data from ORNL (1986) and EON/EIRP (2017)





Low to Moderate Granularity
(5-10 categories)

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Overnight Construction Cost (OCC) Ranges

Proposed Targets/ Assumptions for OECD Countries (NOAK)

- Nominal $5500/kWe
- Low Cost $4000/kWe (~25% reduction)
- Very Low Cost $2500/kWe (~50% reduction)
  - Potentially achieved today in non-OECD markets and Korea (OECD country)

Desirable outcome would be to identify individual or cumulative cost reductions on the order of *at least* 25% (<$4000/kWe)

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Brief Summary of Project Tasks

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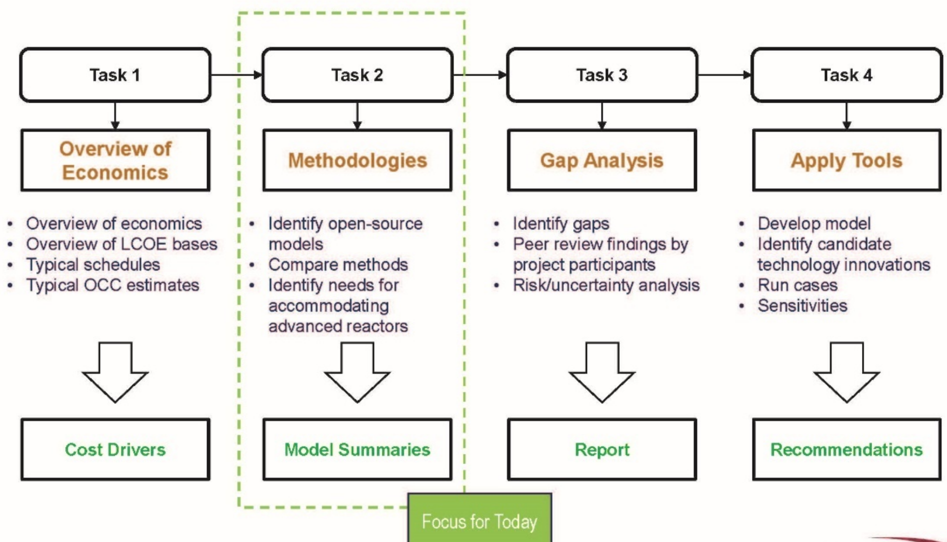
Individual Project Tasks



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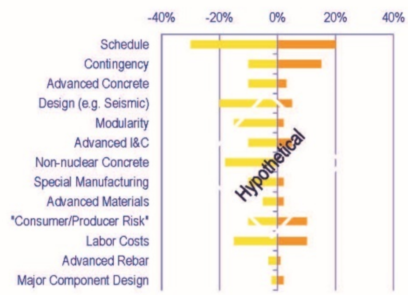
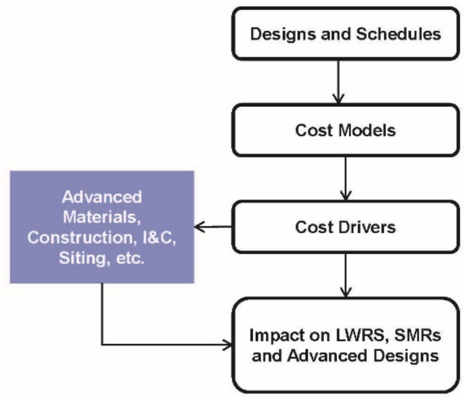
Hypothetical Model Execution (simplified)

- Inputs include plant size, country (labor rates), N-pack, FOAK/NOAK, schedule, etc.





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Summary of Past Cost Models

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Summary

- ~60 models and references reviewed so far
- References/models from 7 countries
- 11 selected for comparison
  - Assumptions
  - Scope (Gen III, advanced reactors, etc.)
  - Approach
  - Source of data
  - Results
  - Conclusions

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Example Cost Evaluation Studies/Tools

- EEDB (DOE)
- G4ECONS (EMWG of OECD/NEA)
- NEST
- Utility
- NSSS
- EPC
- Universities
- Investors (Wall Street)

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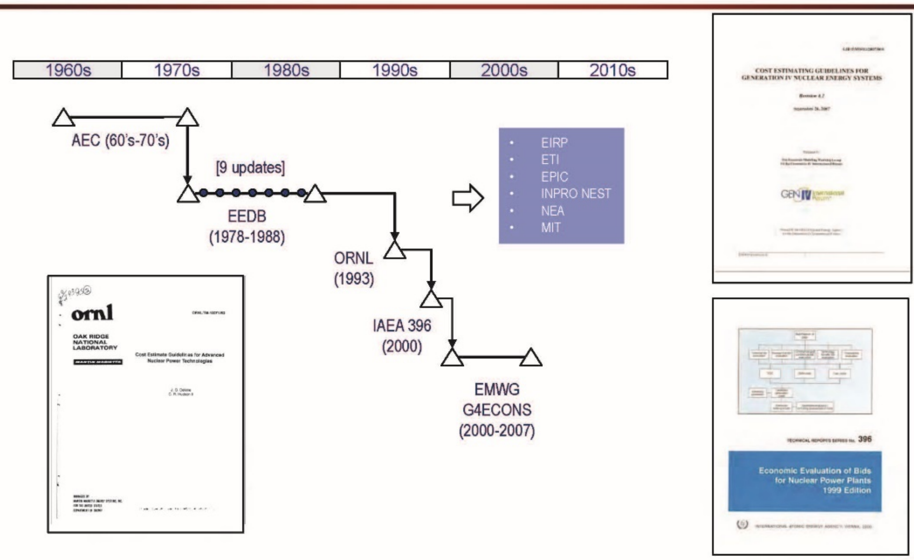
Timeline of Several Economic Tools



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More Recent Investigations

- Historical costs (Lovering, et al.)
- Expert elicitation (Baker, Anadon)
- EPIC
- ETI
- EIRP

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Comparison of Cost Studies and Models

		1	2	3	4	5	6	7	8	9	10	11
	Organization	DOE	OECD	ORNL	AEA	Univ Chicago	B&V	Breakthrough	EON	Cleantech	ANL (Ganda)	OECD
	Name	EEDB	G4ECONS	Guidelines	396	EPIC	Cost Report	EP	EIRP	ETI	ICAAP	Reduced Cap
	Year(s)	1978-1988	2000-2007	1993	2000	2004/2011	2012	2016	2017	2018	2016	2000
Revisions/Updates		9	Several			1						
Plant Designs	PWR	•	•	•	•	•	•			•	•	•
	BWR	•	•	•	•	•	•				•	•
	PHWR	•	•	•	•		•					•
	Advanced Nuclear	•	•	•					•	•		•
	Fossil	•		•			•					
	Total Number	33	>6	>6	Guideline	5	15	349	8	33	4	>18
Maturity	Existing	•	•	•	•	•	•			•	•	•
	Future	•	•	•					•	•		
Methodology	Bottom Up	•	•		•	•	•			•		•
	Top Down									•		•
Siting		Generic	Specific	Generic	Specific	Specific	Generic	Specific	Generic	Specific	Generic	Specific
Analysis	OCC	•	•	•	•	•	•	•	•	•	•	•
	DC	•	•	•	•	•	•	•	•	•	•	•
	Indirect Costs	•	•	•	•	•			•	•	•	•
	Labor-hours	•	•	•					•			
	Owners Cost		•	•	•	•	•			•	•	•
	TCIC		•	•	•	•	•		•	•		
	LCOE (LUEC)		•	•	•				•	•	•	
	IDC		•	•	•				•	•	•	
	Fuel Cycle		•	•	•							
COA	Yes/No	Yes	Yes	Yes	Yes	Yes	Proprietary	No	Yes	Yes	Yes	Yes
	n-Digit	Up to 9	3-6	Up to 6	2 to 3	2	Unknown		3	3	3	2
Data Source	Experience	•	•	•	•	•	•			•	•	•
	Public	•	•	•	•	•		•		•	•	•
	Engineering	•	•	•								•
	Utility	•	•	•		•		•		•	•	•
	Vendor	•	•	•					•			•
	Expert Elicitation	•	•			•				•		•
	Proprietary	•	User Input				•		•			
Schedule Analysis		Limited	User Input	User Input			•					

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Top-Down Approach

- Rules for cost estimating based on historical data
  - $/HP pump, $\$/ft^3$ for vessel, etc.
- More appropriate for new concepts/designs
- Very common in chemical process industry
  - Requires basic flowsheets
- Formulas based on equipment size/capacity
  - $Cost(\$) = A + (B \times P^n)$
  - A = Fixed component
  - Base price for reference
  - P^n = scaling factor

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Bottom – Up Approach

- More appropriate for mature designs
  - Up to 10-12 man-years of effort
  - Material take off (MTO) from drawings
  - Build to print
  - Thousands of line items (up to 20 million parts)
- Typically requires
  - P&IDs
  - SDDs
  - Detailed project plan/WBS
  - Unit work hour data

Goal of this project is to use bottom up costing when possible by building upon existing, open source examples

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Cost Accounting by COA

- COA = Code of Accounts
  - Standardized and well accepted approach
- Can be refined to include material, commodities, labor at extreme level of detail (up to 9 "levels")
- Nine high level categories (e.g., EEDB – see later slides)
  - 10 to 60 – Direct capital costs with labor associated with that item
  - 70 to 90 – Indirect costs

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Terminology

- Direct Costs (DC)
- Indirect Costs
- Total Capital Investment Cost (TCIC)
  - Sometimes includes first core
  - Sometimes includes owners costs
- Interest during Construction (IDC)
- Owner's costs
  - Capitalized operations, supplementary costs, capitalized financial costs
- Standard unit work hours
  - Person-ours per yd concrete, etc.

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High Level Roll up of COAs

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

EIRP ENERGY INNOVATION REFORM PROJECT

Direct Cost Accounts

EEDB (EMWG)	Category
21	Structures and Improvements
22	Reactor Plant Equipment
23	Turbine Plant Equipment
24	Electric Plant Equipment
25 (26)	Main Condenser/Heat Rejection System
26 (25)	Miscellaneous Plant Equipment
27	Special Materials
28	Simulators

Indirect Cost Accounts

EEDB (EMWG)	Category
91 (36)	Construction Services
92 (34)	Engineering Home Office Services
93 (37)	Field Supervision and Field Office Services

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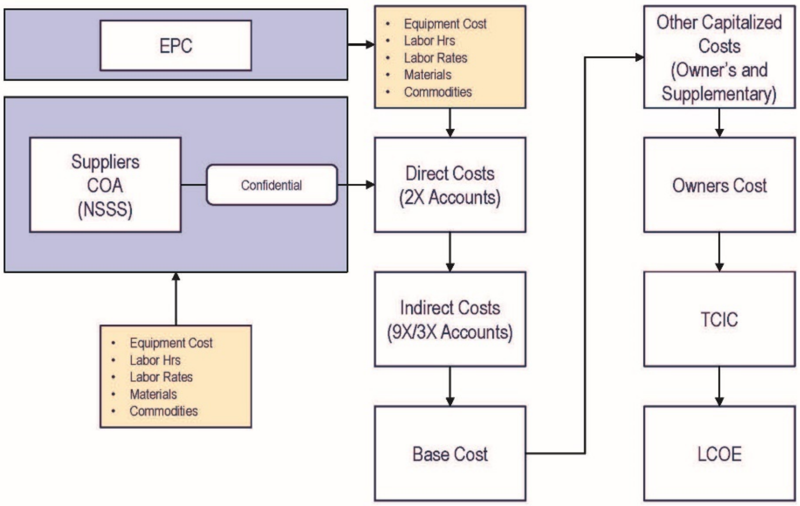
Cost Calculations



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Examples [EEDB and EWMG]

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EEDB

- Multi-year program to inform DOE
  - Began under AEC sponsorship in 1960s (NUS, 1969)
  - Total of 23 years of analysis
  - Nine phases or updates from 1978 to 1988
- 33 power plant configurations in total over 10 years
  - ~8 nuclear configurations
- Code-of Accounts System (up to 9-digit)
  - Assumed that all electric stations have same basic features at two to three digit level
- Direct Cost Accounts (linked to SDDs)
  - Commodities (concrete, rebar, piping, wiring)
  - Components
  - Equipment
  - Installation man-hours

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EEDB (cont.)

- 400 subsystems
- 50 major groups
- 10,000 input "cells"
- Median (ME) and "better" experience (BE)

- No contingency
- No IDC
- No escalation

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EEBD: 1978-1988

- Source of Data – vendor, utility, A/E, some proprietary
- Comparisons to Fossil Plants
- Update VIII (1987)
  - PWR•ME: 1980's vintage
  - PWR•BE: 1990's plant with advanced features
- Update IX (1988)
  - PWR 12 (replaces PWR•BE) (1144 MWe) – anticipated technology maturity in 2000
  - PWR 6 (587 MWe)
  - 3.9% higher in excess of inflation from XIII to IX
- Additional goal of identifying features for advanced reactors to lower cost

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EEDB Phase IX (1988)

- New Models
  - IPWR12 (modular, standard design) – *lowest cost (17% lower than PWRBE)*
  - PWR6 BE (two loop, standard "better" cost basis)
  - IPWR6 (modular, standard design)
  - APWR6 (modular, standard design, passive safety)
- PWR6 Costs 30% higher per kWe than PWR 12
  - Scaling factor of n= 0.52
- PWR12•BE = $1272/kWe
- IPWR12 = $1056/kWe

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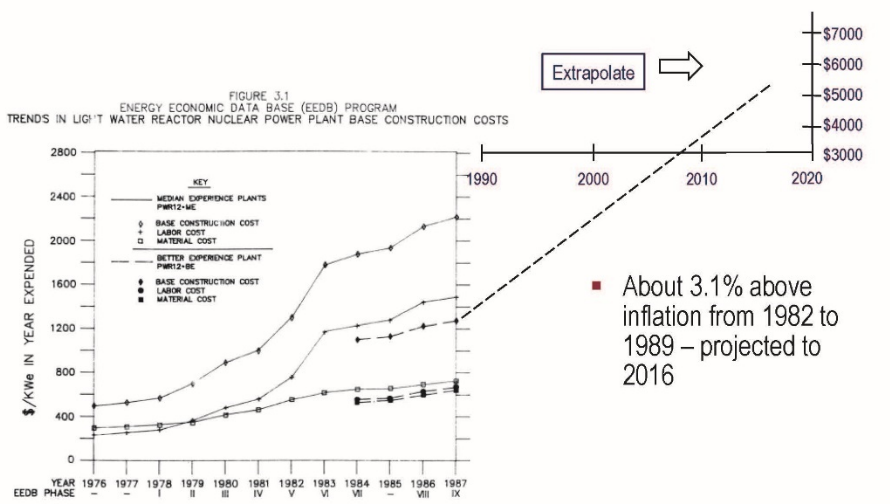
EEDB Caveats

- Does not include modern IT
- Does not reflect post 9/11 security
- Non-conservative
  - Training facilities
  - EOC
  - Post 9/11 upgrades
  - QA/QC
- Conservative
  - Home office/site office

EEDB Trends and Extrapolation



- About 3.1% above inflation from 1982 to 1989 – projected to 2016

EEDB Cost Drivers

- Commodities, equipment, equipment manhours
- Example
  - Craft man-hours and indirects increased 220% above inflation over course of project

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EMWG: 2003-2007

- Standard cost estimating protocol for GenIV Reactors
  - Advanced reactor focus
- Established EMWG in 2003
  - Concurrent to DOE GenIV Roadmap
- Open-source Code G4-ECONS
- Structure
  - Construction/production
  - Fuel cycle
  - Energy products
  - Modularization
- Standard COA (aka GIF COA)
- Standard cost estimating methodology

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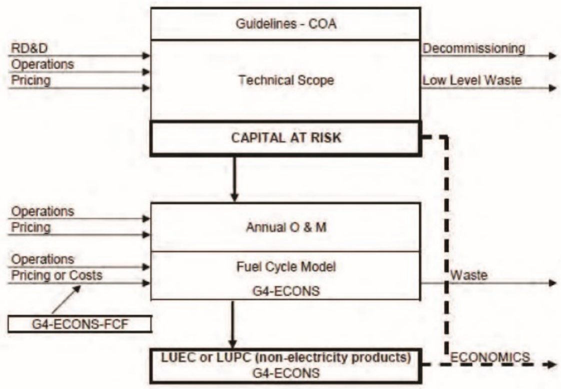
EMWG (cont.)

- Limited to 2-digit level
  - To protect proprietary information



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IAEA (2000)

- Guidelines for utilities in assessing bids
  - Conventional and advanced reactors
  - Bid Invitation Specification (BIS)

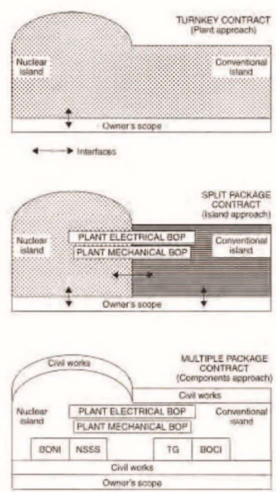

FIG. 3. The three types of contract. NSSS: nuclear steam supply system; BOCI: balance of conventional island; BONI: balance of nuclear island; BOP: balance of plant; TG: turbine generator.

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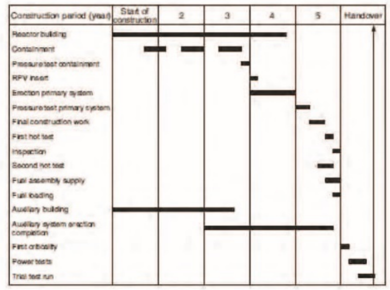
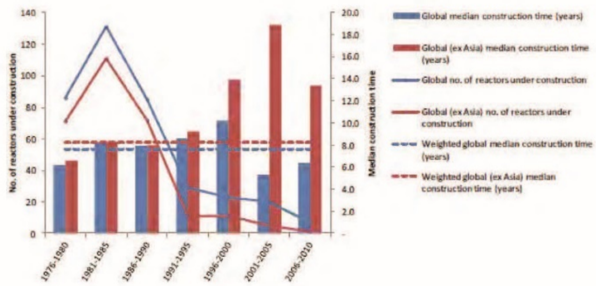
Schedules

- Benchmark and schedules provided in several studies



MW(e) NPP.



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Plans - Modeling Tasks 3 and 4

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Overview

- Build upon existing codes/methods
  - More efficient
  - Amenable to peer review
- Three examples (TBD)
  - EMWG PWR 12 (or iPWR)
  - One advanced reactor (HTGR?)
  - One SMR (if data accessible)
- For-Information-Only
  - Not “software”

Overview (cont.)

- Minimum 3-digit COA
- Includes separate evaluations/modules for:
  - Direct and Indirect costs
  - Materials and commodities
  - Labor
- Country specific with respect to:
  - Labor rates
  - Labor productivity
  - Materials and commodity costs

Sources of Cost Data

- Dozens of potential sources of costs
  - EEDB
  - ORNL
  - EIA
  - EPRI
  - G4-ECONS
  - Literature
  - PUC/PSC Disclosures
  - IAEA
  - Unions
  - Utility filings
  - Vendors
  - NGNP Studies
  - GEN-IV
  - Academic studies
  - Outside Experts
  - Investor analysis
  - Early experience (1970s to 1990s)

Direct and Indirect Costs

- Derived from EMWG COA with EEDB Data (PWR12 BE)

Summary of Code of Accounts PWR12-BE EEDB Phase IX

Base Year	1987
Current Year	2016
ENR Cost Multiplier	2.50
Gross Mwe	1144

Direct Costs	Two-Digit Code of Accounts (COA) EEDB	IAEA	EMWG	Scope	Purpose	Examples	Three-Digit Code of Accounts EMWG	Scope COA	Unit Cost per kWe Factory Equipment	Site Labor Hours (man-hrs)	Site Labor Cost	Site Materials	Total Cost
	20		10	Preconstruction Activities	Secure rights and permission to construct the plant	• Land and land rights	10	Total Cost	$/kW	MH/kW	$5/kW	$/kW	$6/kW
						• Site permits			$/kW	MH/kW	$5/kW	$/kW	$6/kW
						• Plant licensing			$/kW	MH/kW	$/kW	$/kW	$/kW
						• Plant permits			$/kW	MH/kW	$/kW	$/kW	$/kW
						• Plant studies			$/kW	MH/kW	$/kW	$/kW	$/kW
						• Plant reports			$/kW	MH/kW	$/kW	$/kW	$/kW
							TOTAL		$/kW	MH/kW	$5/kW	$/kW	$6/kW
	21	21	21	Structures and Improvements	House and support equipment, components, piping, ducting, wiring, fire protection, MEP, personnel, access, habitability structures	• On-Site Surface Buildings	21	Total Cost	$40/kW	5 MH/kW	$248/kW	$141/kW	$438/kW
						• Subsurface Foundations	211	Yardwork	$1/kW	1 MH/kW	$32/kW	$22/kW	$55/kW
						• Tunnels	212	Reactor Containment	$31/kW	1 MH/kW	$78/kW	$33/kW	$141/kW
						• Site Improvements	213	Turbine Bldg and Heater Bay	$1/kW	MH/kW	$24/kW	$25/kW	$51/kW
						Clearing	214	Security Bldgs	$/kW	MH/kW	$2/kW	$1/kW	$3/kW
						Excavation	215	Prim Aux Bldg and Tunnels	$7/kW	MH/kW	$23/kW	$10/kW	$40/kW
						Grading	216	Waste Processing Building	$1/kW	MH/kW	$20/kW	$10/kW	$31/kW
						Roadways	217	Fuel Storage Building	$2/kW	MH/kW	$10/kW	$10/kW	$22/kW
						Rail Spurs	218A	Control Room/DG Bldg	$3/kW	MH/kW	$24/kW	$12/kW	$39/kW
						• Buildout/detailing	218B	Admin and Service Bldg	$2/kW	MH/kW	$7/kW	$5/kW	$15/kW
						• Does not include	218D	Fire Pump House	$/kW	MH/kW	$1/kW	$/kW	$1/kW
						Equipment Pedestals	218E	Emergency Feed Pump Bldg	$/kW	MH/kW	$4/kW	$2/kW	$5/kW
						Heat Reject Bldg	218F	Manway Tunnels (RCA)	$/kW	MH/kW	$1/kW	$/kW	$2/kW
							218G	Electrical Tunnels	$/kW	MH/kW	$/kW	$/kW	$/kW
							218H	Non-Essential Switchgear	$/kW	MH/kW	$1/kW	$/kW	$1/kW
							218I	Main Steam and FE Chases	$/kW	MH/kW	$12/kW	$6/kW	$17/kW
							218K	Pipe Tunnels	$/kW	MH/kW	$/kW	$/kW	$1/kW
							218L	Tech Support Center	$/kW	MH/kW	$1/kW	$1/kW	$2/kW
							218P	Equipment Hatch Missile Shield	$/kW	MH/kW	$/kW	$/kW	$/kW
							218S	Wastewater Treatment	$/kW	MH/kW	$1/kW	$1/kW	$2/kW
							218T	UHS Structure	$/kW	MH/kW	$7/kW	$3/kW	$10/kW
							218V	MCR Air Intake Structure	$/kW	MH/kW	$/kW	$/kW	$/kW

Materials and Commodities

- Multiple open sources
- Validation from expert elicitation envisioned

Category	Item	Unit	EEDB PWR12
Commodities	Excavation	CY	491,000
	Formwork	SF	1,886,000
	Reinforcing, Embedded and Structural Steel	TN	29,000
	Structural Concrete	CY	132,000
	BOP Pumps (excludes RCPs)	HP	58,000
	Piping	LB	9,163,000
	Raceways	LF	672,000
	Wire and Cable	LF	4,979,000
Equipment	NSSS	Lot	$167/kW
	Turbine Generator	Lot	$112/kW
	Heat Exchangers	Lot	$48/kW
	I&C	Lot	$30/kW

Labor Costs

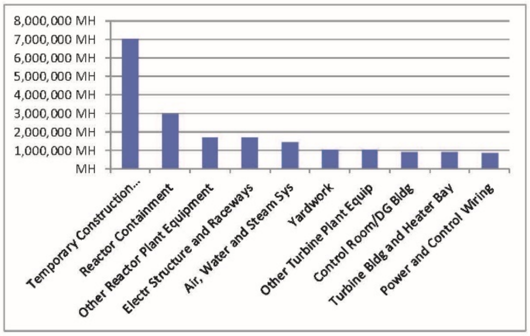
- Country specific
- Variable include wages/OH/fringe, N-pack, productivity

Productivity Improvements in Standardized Design (UE&C)

	Rel MH (distibuted CS)	Category	Units	Plant 1	Plant 2	Plant 3
Structural Craft	0.81	Structural Concrete	MHRS/CY	1	-9%	-10%
		Form Work (carpenters)	MH/SF	1	-17%	-37%
		Rebar Installation	MHRS/CY	1	-10%	-28%
		Placement	MHRS/CY	1	-16%	-22%
		Structural Steel	MH/TON	1	-3%	-24%
Mechanical Craft	0.29	Small Bore pipe	MH/EA	1	46%	16%
		Large Bore Pipe	MHR/LF	1	10%	-21%
		Large Bore Hangers	MH/EA	1	10%	-21%
Electrical / I&C Craft	0.20	Conduit	MH/LF	1	115%	103%
		Cable Trays	MH/LF	1	-19%	-22%
		Cable and Wire	MH/LF	1	0%	142%
		Electrical Termination	MH/EA	1	-30%	-26%
		I&C	MH/EA	1	-5%	-23%
			Net Saving	**1**	**2%**	**-13%**

Note: Weighted by Fraction of Labor per EEDB Study

Top 10 Labor Activities



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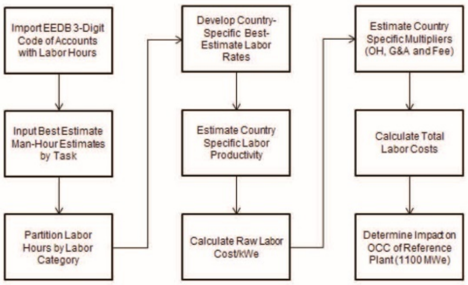
Labor Model Logic



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Labor Worksheet

Scaling MWe

Roughly the EPIC numbers

Learning Curve/ No Learning Curve

Relative Workers On Site

Assumed % labor

United Stated		4000	$/kWe		1.00	Currency	(1986 to 2016)		
		25%	Total Labor						
		0.61	Prod Factor (US)						
		1144	Base Power						
								Scaling	0.967
						MW	1200	N-Unit	2
		OCC	Directs	Labor	Prod Factor	Labor Cost			Net
		$ 4,000	$ 3,000	$ 1,000	0.61	($/hour)	LC/NLC	WOS	$ 864.05
Structural Craft	SC	0.107			0.61	$51	1	1	$ 92.17
Mechanical Craft	MC	0.137			0.61	$44	1	1	$ 118.35
Electrical / I&C Craft	EC	0.053			0.61	$35	1	1	$ 45.56
Construction Services	CS	0.114			0.61	$35	1	1	$ 98.45
Engineering	E	0.271			0.61	$62	1	1	$ 234.08
Field Supervision	FS	0.212			0.61	$88	1	1	$ 182.76
Admin	O	0.038			0.61	$12	1	1	$ 32.99
Insurance and Taxes	I&T	0.069			0.61	$25	1	1	$ 59.70
		Fraction						Total	$ 864.05

EEDB Study Fractions

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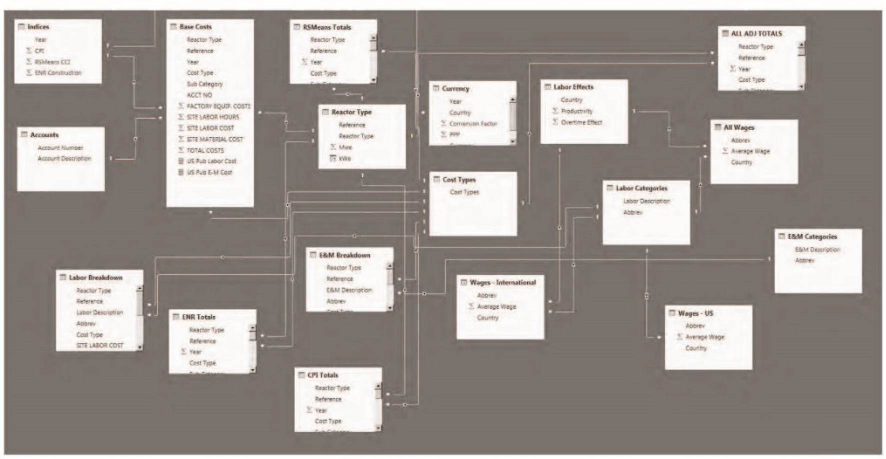
Model Structure (Tasks 3 and 4)



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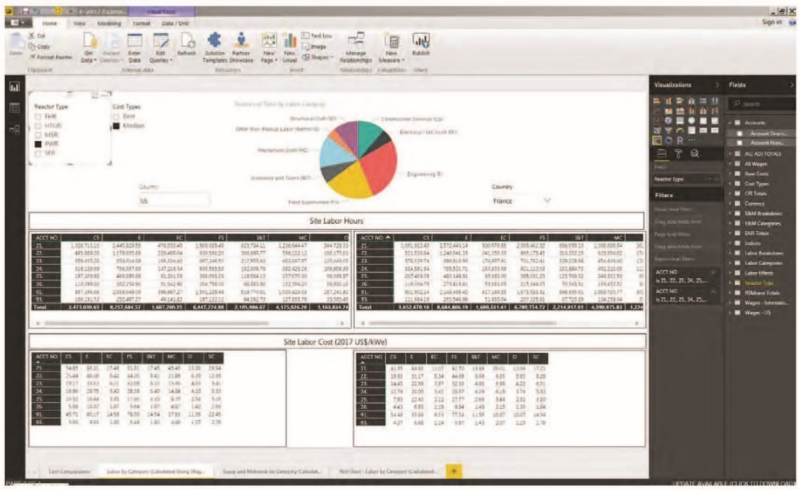
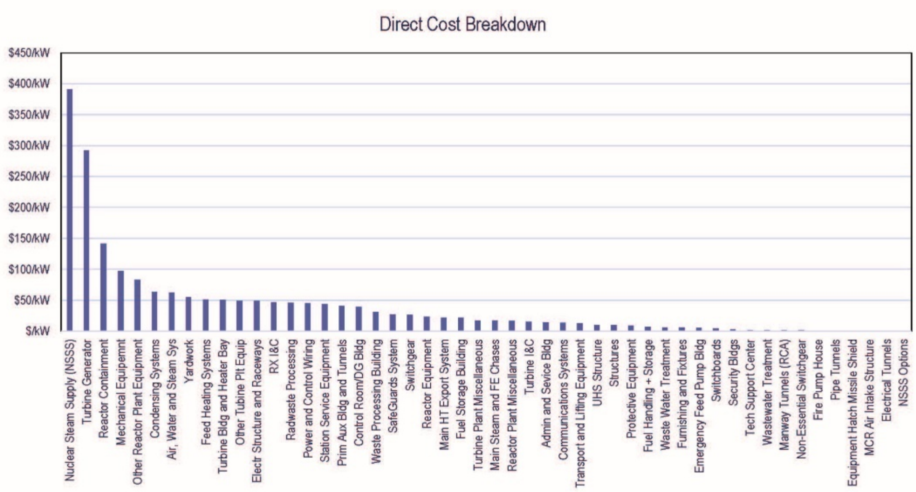
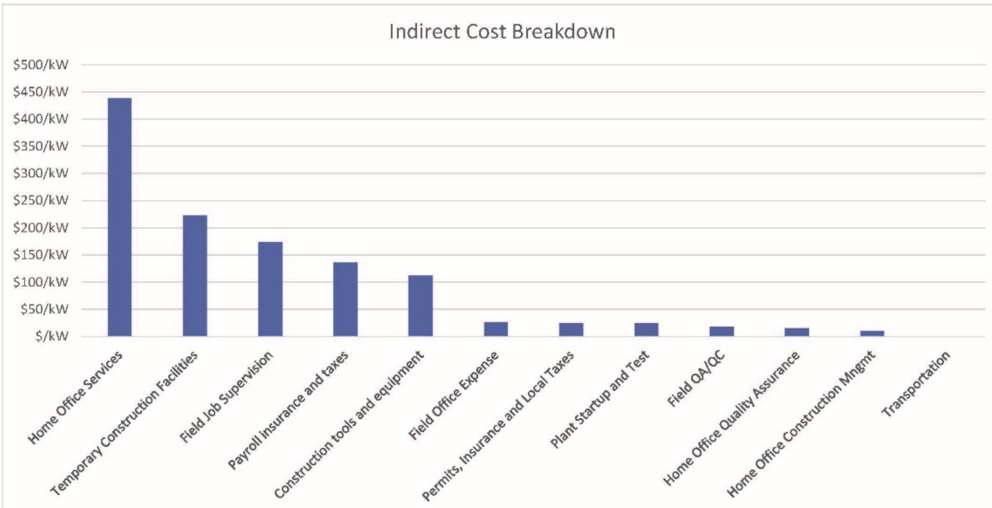
Dashboard



Example Direct Costs



Example Indirect Cost Breakdown



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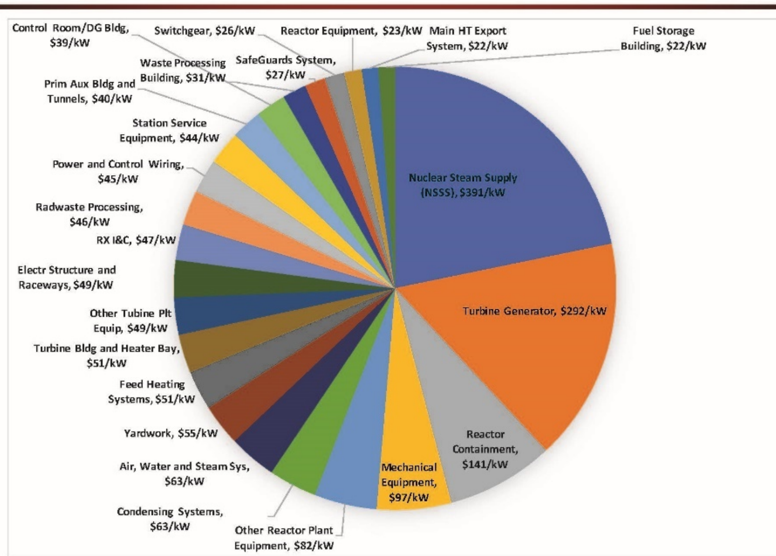
Direct Cost Pie Chart (all items>1%)



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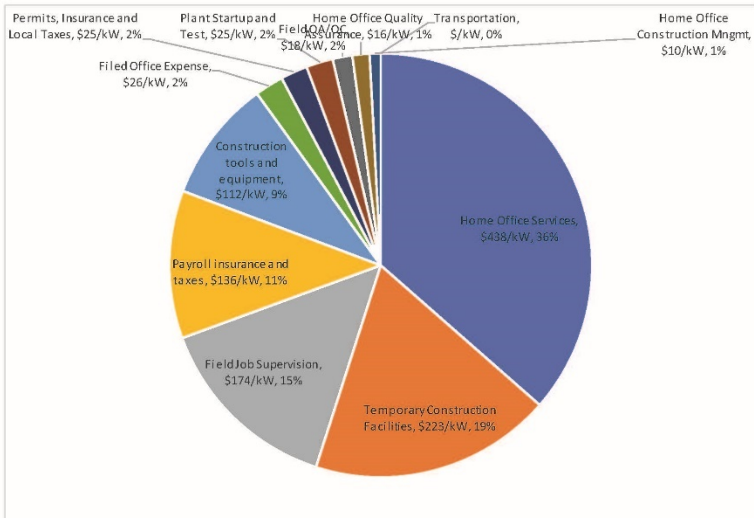
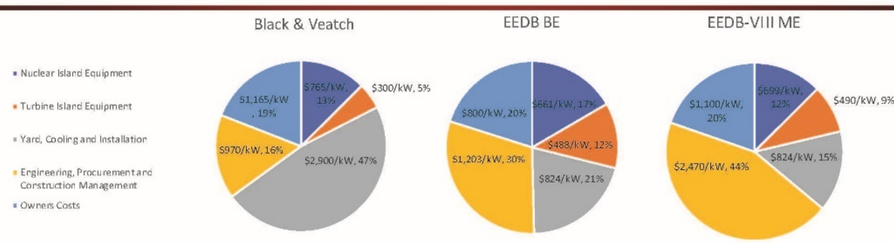
Indirect Cost Pie Chart (all items)

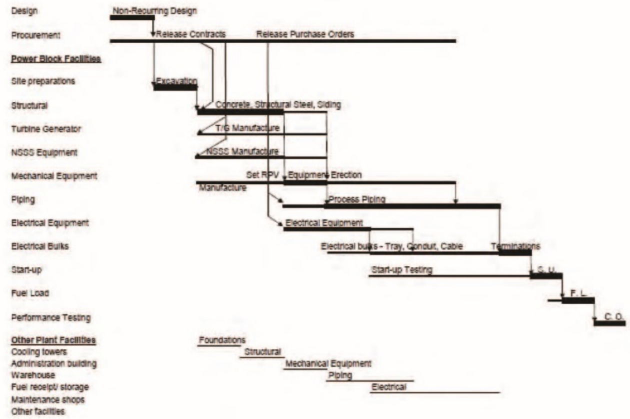


Comparison of Pie Charts



EEDB Codes	Scope	B&V (2009)		EEDB IX-BE (1988 adjusted)		EEDB VIII-ME (1987 adjusted)	
		Cost	Percent	Cost	Percent	Cost	Percent
22	Nuclear Island Equipment	$765/kW	13%	$661/kW	17%	$699/kW	13%
23	Turbine Island Equipment	$300/kW	5%	$488/kW	12%	$490/kW	9%
21, 24, 25, 26	Yard, Cooling and Installation	$2,900/kW	48%	$824/kW	21%	$824/kW	15%
91, 92, 93	Engineering, Procurement and Construction Management	$970/kW	16%	$1,203/kW	30%	$2,470/kW	44%
	Owners Costs	$1,165/kW	19%	$800/kW	20%	$1,100/kW	20%
	Total	$6,100/kW	100%	$3,976/kW	100%	$5,583/kW	100%

Example Schedule



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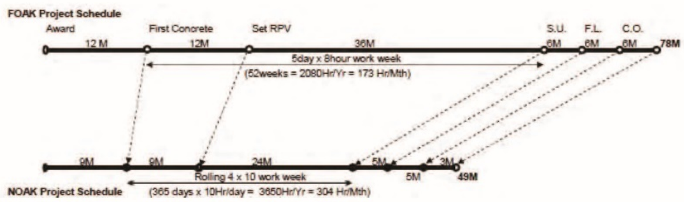
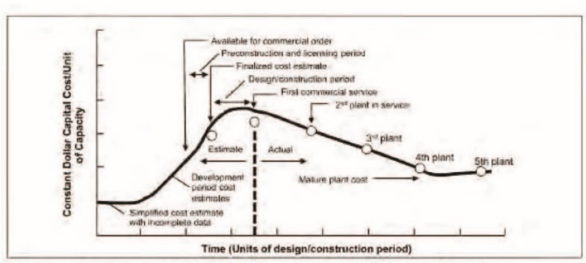
FOAK to NOAK Improvement





Source: *EPRI Program on Technology Innovation: Integrated Generation Technology Options*, June 2011.

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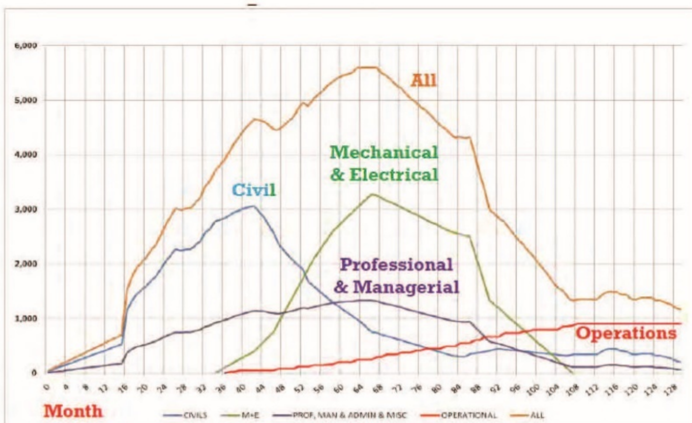
Nuclear Construction Manpower



Source: **EDF, "Hinkley Point C, Development Consent Order Application: Accommodation Study," October 2011. https://www.edfenergy.com/file/1662/download** 7

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Effect of Construction Time on Indirects

Duration (mos)	Indirect Costs			
	Nuclear Island	BOP	Total	Impact
36	$ 427,455,664	$ 388,576,257	$ 816,031,921	$713/kW
48	$ 567,693,279	$ 515,872,257	$ 1,083,565,537	$947/kW
60	$ 707,930,895	$ 643,168,257	$ 1,351,099,152	$1,181/kW
72	$ 848,168,511	$ 770,464,257	$ 1,618,632,768	$1,415/kW
84	$ 988,406,126	$ 897,760,257	$ 1,886,166,384	$1,649/kW
96	$ 1,128,643,742	$ 1,025,056,257	$ 2,153,699,999	$1,883/kW
108	$ 1,268,881,358	$ 1,152,352,257	$ 2,421,233,615	$2,116/kW
120	$ 1,409,118,974	$ 1,279,648,257	$ 2,688,767,231	$2,350/kW

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Next Steps

- Continue Work on Tasks 1 and 2
  - Finish benchmarking past studies
  - Draft a set of criteria and merits (attributes such as schedule, productivity, simplicity, material and commodity quantities, standardization, streamline work packages, crosscutting innovations, etc.)
- Gap analysis
- Propose quantitative model correlations for economic assessments
- Expert elicitation (to supplement what has been done)
- Develop and apply evaluation tools
- Case studies

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Project Schedule

- Expert Elicitation Meetings/Telecons
  - June, July, August 2018
- Task 1 and 2 (Overview and Summary of Past Methods)
  - September 2018
- Task 3 (Gap Analysis and Recommended Modeling)
  - November 2018
- Task 4 (Model Application)
  - December 2018

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