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Light Water Reactor Sustainability Program

A Review of Light Water Reactor Costs and Cost Drivers

Karen Dawson and Piyush Sabharwall

September 2017

U.S. Department of Energy
Office of Nuclear Energy

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Light Water Reactor Sustainability Program
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SUMMARY

Nuclear power plays a significant role in electricity generation in the United States (U.S.) and has four main value propositions:

- Diversity: Nuclear power adds another generation source to the U.S. power-generation mix. Diversity is important in power generation because individual generation sources often have high uncertainty in future prices (due to fuel costs, supply issues, etc.). By maintaining a diverse portfolio, price volatility can be minimized.
- Reliability: Nuclear power is not subjected to potential supply interruptions (such as natural gas). The value of nuclear power's reliability is shown clearly in the events of the 2014 Polar Vortex when many U.S. natural-gas power plants were unable to produce electricity due to supply constraints.
- Sustainability: Nuclear power has a small land footprint per unit of energy produced. In addition, there are no significant emissions produced during generation of electricity from nuclear.
- National Security: Having a successful nuclear power plant fleet allows the U.S. to maintain its role as a leader in nuclear technology and policy. In this role, the U.S. has a significant influence on international nuclear policies, particularly non-proliferation technology.

Even though nuclear power is viewed as a valuable part of the electricity-generation portfolio, the current domestic nuclear fleet is in a precarious position. Low wholesale electricity prices, driven down by a natural-gas production boom since 2006, are often lower than the operating and maintenance cost of a nuclear power plant. This economic situation is forcing plants to close prematurely (before expiration of their operating licenses). In addition, the cost of nuclear power is composed primarily of its very high initial capital cost. This high barrier has led to very little new nuclear construction. Since the rate of nuclear power plant closures is greater than the rate of new construction, the U.S. is faced with the possibility of a decrease in the nuclear power plant fleet. This situation motivates us to examine the predominant cost drivers of nuclear power plants to determine where costs can be reduced.

Analysis of published historic cost breakdowns of LWRs in the U.S. shows that the **main cost driver is not the nuclear technology itself; rather, it is the cost of a large-scale construction project that is regulated by strict nuclear standards.**

A complete analysis of LWR commodity labor and material costs is presented. Commodity costs are influenced by many factors, including labor rates, installation times, physical location of their use onsite, and quality (nuclear versus non-nuclear). The overall cost of concrete comprises 58% labor and 42% materials. The cost of steel comprises 32% labor and 68% materials. A parametric analysis performed on the installation times of both concrete and steel indicates that cutting the installation times in half reduces the total cost of concrete and steel by 29% and 16%, respectively. In addition, the cost burden of having strict quality-control standards (i.e., the nuclear premium) was quantified for concrete and steel. For concrete, the nuclear premium represents 23% of the

total concrete cost. For steel (including rebar), the nuclear premium represents 41% of the total steel cost.

In addition, a simple analysis of the effect of reactor-plant size and learning rate of first-of-a-kind (FOAK) costs is presented. A FOAK premium is calculated as the additional costs incurred over the nth-of-a-kind (NOAK) costs for construction of a new reactor design. **It is found that the smaller the reactor size, the smaller the overall FOAK premium because NOAK is reached at a smaller total installed capacity.** In addition, it is found that the FOAK premium decreases as learning-rate increases. This implies that there is a financial incentive to invest in learning (keeping the same construction crew, optimally spacing the construction of subsequent units, implementing lessons-learned policies across the industry, etc.) when a new reactor design is deployed.

Three main areas of future research are identified along with some recommendations. The three areas of research are

- Rank new construction innovations in terms of their ability to be constructed and to reduce costs in a nuclear construction. This approach requires construction management experts to be included in this research for it to be meaningful.
- Evaluate new designs for their feasibility of construction (“constructability”). This includes both ease of construction at the site and ease of fabrication and assembly of system components.
- Perform a cost-benefit analysis of the nuclear premium. It is clear that the nuclear premium adds a significant burden to the cost of construction. This burden needs to be justified. If it cannot be justified, then the burden needs to be reduced.

Overall, the recommendation of this report is to analyze construction of a nuclear power plant over the technology itself when performing cost analyses of nuclear power. The most significant cost reductions will come from reducing the cost of construction. This can happen in several ways, for example by reducing the amount of materials needed or increasing the productivity of workers. In proposing new nuclear designs with the purpose of cost reduction, construction costs should strongly influence the design decisions.

ACKNOWLEDGEMENTS

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ACRONYMS

CSP	concentrating solar power
EIA	U.S. Energy Information Administration
EMWG	Economic Modeling Working Group
FOAK	first-of-a-kind
IAEA	International Atomic Energy Agency
LCOE	levelized cost of electricity
LWR	light water reactor
NEA	Nuclear Energy Agency
NERC	North American Electric Reliability Corporation
NOAK	nth-of-a-kind
NPT	Treaty on the Nonproliferation of Nuclear Weapons
O&M	operation and maintenance
PV	photovoltaic
PWR	pressurized water reactor

NOMENCLATURE

P	Power
hp	Horsepower
$\dot{m}$	Mass Flow Rate
ΔP	Pressure Rise
η	Efficiency
ρ	Density
$\dot{Q}_{th}$	Thermal Power
c	Specific Heat
ΔT	Temperature Rise / Temperature Difference
A	Area
U	Overall Heat Transfer Coefficient

A Review of Light Water Reactor Costs and Cost Drivers

1. Role of Nuclear Power in the U.S. Energy Mix

The United States (U.S.) generated around 4,000 terawatt-hours of electricity in 2016. Of this generation, around 800 terawatt-hours (20%) was produced through nuclear power (U.S. Energy Information Administration [EIA] 2017b). The average capacity factor of U.S. nuclear power plants in 2016 was 92.5% (EIA 2017a). Nuclear energy has many important roles in the U.S. power generation mix. The role of the government is to support research and development of new nuclear technologies as well as to create policies to support nuclear deployment. This report investigates areas for research and development that have the potential to have a significant effect on cost reduction of nuclear power production.

1.1 Benefits of Nuclear Power Generation

There are many benefits of having nuclear power generation as part of the U.S. energy mix. Increasing the diversity of the energy mix reduces the impact of a resource scarcity on energy supply and pricing. In addition, having a power generation source with high reliability reduces the impact of external events on energy supply and pricing. Power is generated from nuclear power plants without any air pollutants that cause poor air quality and/or accumulate in the atmosphere and contribute to climate change. With 10% of uranium reserves in North America (Nuclear Energy Agency [NEA] and International Atomic Energy Agency [IAEA] 2016), nuclear power generation is not likely to be subjected to fuel shortages as a result of political pressures. This is beneficial for national security. In addition, by maintaining a strong nuclear fleet, the U.S. can be the leader in international politics concerning nuclear proliferation.

1.1.1 Fuel Source Diversity

Currently, the U.S. has a diverse energy generation mix, where no single generation source constitutes a majority of the electricity generation (see Figure 1) (EIA 2017b). The value of this diversity is a decreased risk of electricity price escalation. Power generation technologies use different fuels (or for renewable technologies, lack of fuel), and therefore, have different fuel cost risks. Fuel is subjected to various sources of uncertainty, such as future price and future supply. Maintaining a diverse power supply portfolio is crucial to manage this uncertainty and maintain low volatility in the generation cost of electricity, and therefore, a more predictable generation cost of electricity. This is called the portfolio effect which is effective because the fuel costs of different power supplies are not highly correlated (Makovich et al. 2014). If a diverse power supply portfolio is maintained, then as one fuel cost rises, the market can shift to a power supply with a lower fuel cost (in the short run) if this will decrease the cost of generating electricity. This is called the substitution effect. Power suppliers must be dispatchable to provide the substitution effect.

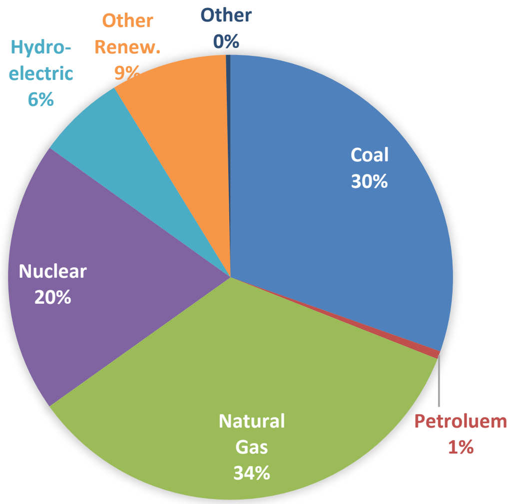

Figure 1. 2016 U.S. energy generation mix (EIA 2017b).

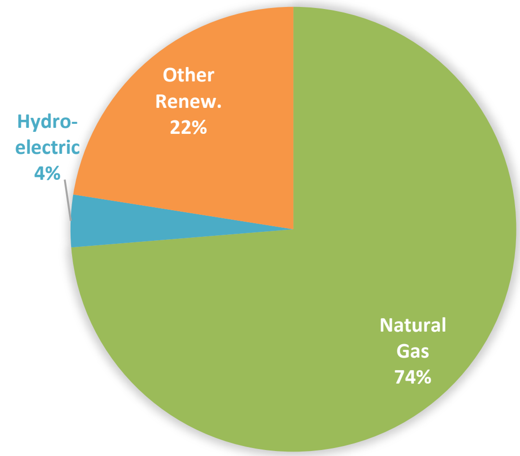

Figure 2. Potential reduced diversity case (Makovich et al. 2014).

A report published by IHS Energy shows that switching from the current energy mix in the U.S. (Makovich et al. 2014) to a reduced diversity case (Figure 2) would increase the average wholesale electricity price by 75% and would result in almost $91 billion of additional cost to electricity consumers (Makovich et al. 2014). **Nuclear energy plays an important role by increasing the diversity of the U.S. energy mix.**

1.1.2 Power Supply Reliability

Different fuels are subjected to different deliverability and infrastructure constraints. For example, natural gas is delivered constantly as needed via pipelines (with limited onsite storage). Coal is delivered daily mainly via rail and barge. Nuclear fuel is typically delivered every 18 months via truck. This is one reason why nuclear power is a reliable source of electricity. It does not depend on a constant supply pipeline or railroad infrastructure. It only requires a shipment of fuel every 18 months. Because of its reliability, nuclear power is an important part of the U.S. electricity generation mix.

The importance of having a reliable generation source is evident in the events from the polar vortex between January 6 and 8, 2014. The North American Electric Reliability Corporation[a] (NERC) performed an analysis of this event. About 35,000 MW were lost at the peak of the polar vortex due to either cold weather or inability to receive fuel. Of this lost capacity, only 3% was nuclear capacity. This is compared to approximately 55% natural gas and 26% coal capacity lost[b] (NERC 2014).

Approximately 15,500 MW of capacity were lost due to fuel supply issues. Due to extreme cold weather (20–30°F below average), there was an increased residential heating demand for natural gas. Residential heating demand is prioritized over power plant natural gas supply, which resulted in gas-fired power plants experiencing a curtailment of fuel supply. In addition, a natural gas compressor located near Belmont, Pennsylvania, experienced an unplanned outage, which resulted in the reduction of natural gas delivery amounting to 1,700 to 2,300 MW of lost generation (NERC 2014).

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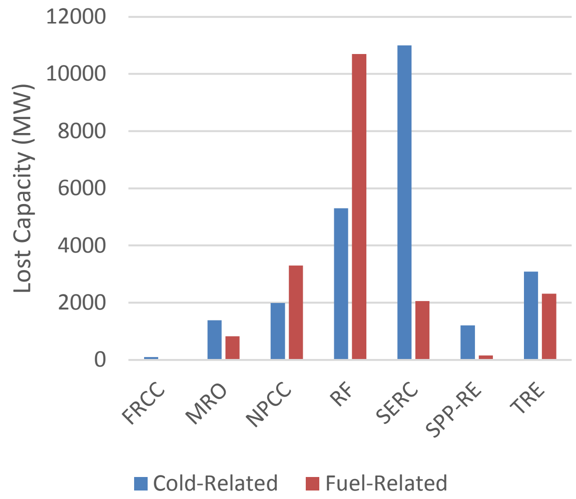
[a] The North American Electric Reliability Corporation is a regulatory body who has the mission to maintain the reliability of the bulk power system in North America.

[b] For reference, the installed capacity percentages are 40% natural gas, 31% coal, and 12% nuclear.

Approximately 19,500 MW of capacity were lost due to the cold weather. Most of this was due to frozen equipment. Issues included frozen sensors, cold air backflow down the stack, frozen circulating water, gelling of fuel oil and diesel fuel, snow/ice covering intakes and blades, etc. For further details on frozen equipment complications, see (NERC 2014). Figure 3 shows causes of cold or fuel related outages for each of the regional entities of NERC. Figure 4 shows where each of the regional entities is geographically located.



FRCC: Florida Reliability Coordinating Council

MRO: Midwest Reliability Organization

NPCC: Northeast Power Coordinating Council

RF: ReliabilityFirst

SERC: SERC Reliability Corporation

SPP-RE: Southwest Power Pool, Inc.

TRE: Texas Reliability Entity

Figure 3. Outages during the 2014 Polar Vortex by cause and region (Western Electricity Coordinating Council is excluded).

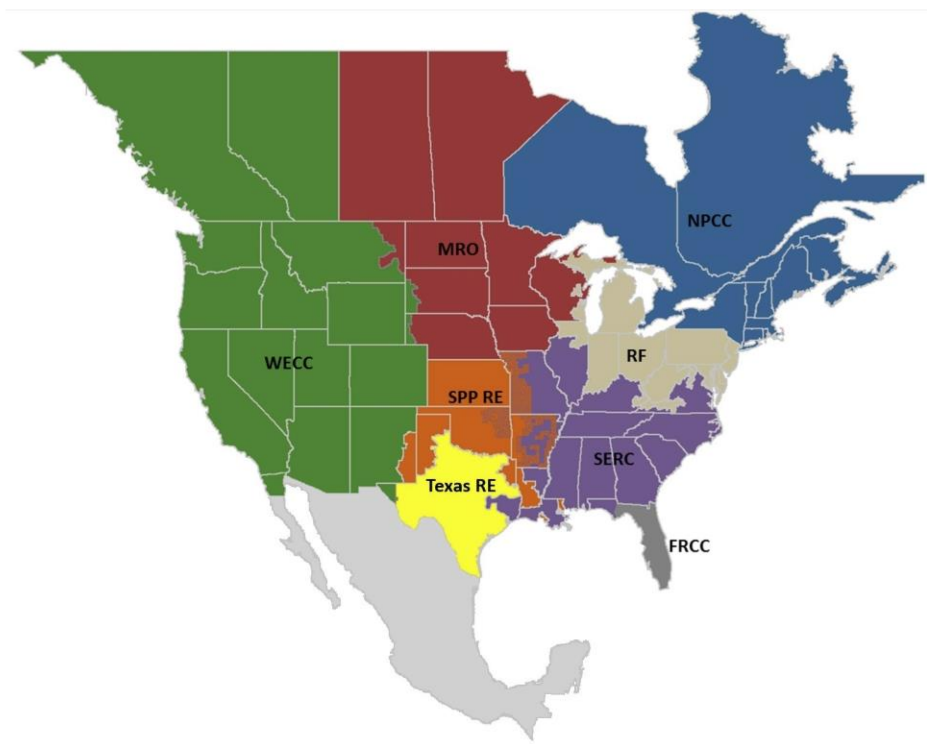


Figure 4. Eight regional entities of Federal Energy Regulatory Commission.[c]

[c] Image from www.nerc.com/AboutNERC/keyplayers/Pages/default.aspx.

1.1.3 Environmental Sustainability

Nuclear power generates electricity with small emissions. Figure 5 shows how lifecycle greenhouse gas emissions vary based on the electricity generation source. The reported values in the chart are median values. The error bars represent the range from the maximum reported value to the minimum reported value (IPCC 2014).

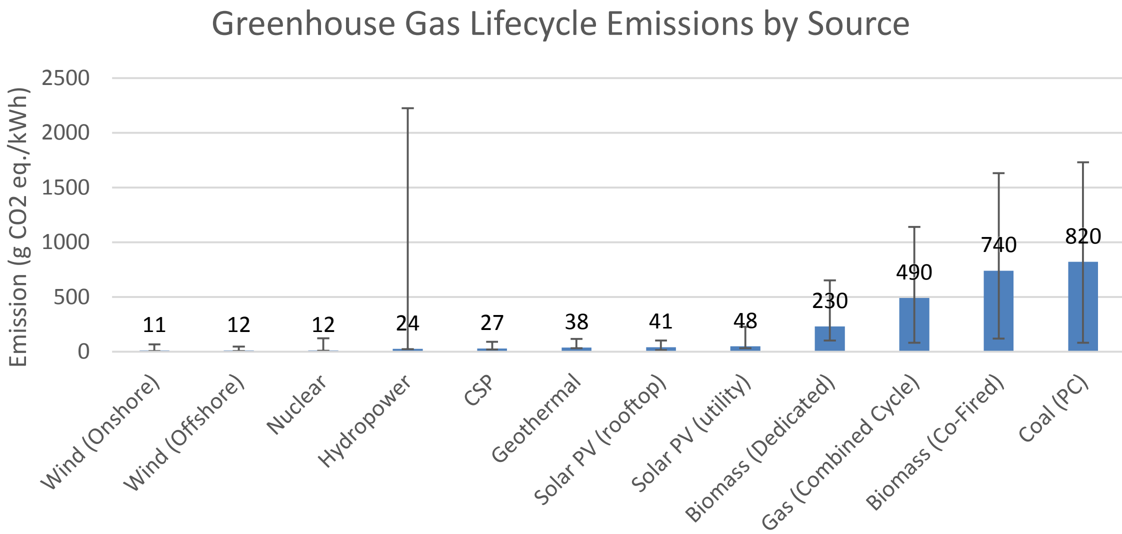


Figure 5. Lifecycle greenhouse gas emission by electricity generation source.

Many power plant emissions are detrimental to air quality. Air pollution can be toxic and has the potential to cause cancer (Environmental Protection Agency 2017). In addition, greenhouse gas emissions build up in the atmosphere and trap heat. This is one leading cause of climate change (Environmental Protection Agency 2017). Nuclear energy can reduce these risks by providing essentially emission-free electricity generation.

1.1.4 National Security

The U.S. has been a leader in global nuclear nonproliferation since Eisenhower gave his “Atoms for Peace” speech before the United Nations in 1953. This speech led to the creation of the International Atomic Energy Agency (IAEA) to ensure that countries honored their commitments to use nuclear power technology for peaceful purposes. In 1970, the Treaty on the Nonproliferation of Nuclear Weapons (NPT) went into effect. Under the NPT, countries without nuclear weapons agreed to not pursue them and countries with nuclear weapons agreed to disarm over time. The IAEA, with U.S. leadership, implemented safeguards to ensure NPT compliance (Energy Futures Initiative, Inc. 2017).

A successful operating nuclear fleet has allowed the U.S. to remain a leader in this global nuclear community. If the U.S. were to exit the nuclear power industry, it can be anticipated that this leadership role will be diminished and eventually replaced by another country. This can already be seen in the Middle East, where Egypt, Jordan, and Saudi Arabia have agreements with Russia for reactor construction and the supply of fuel. U.S. negotiations with these countries under the Atomic Energy Act Section 123, which requires bilateral agreements with countries that receive nuclear technology, were unsuccessful (Energy Futures Initiative, Inc. 2017). Continuing support of the nuclear power industry will allow for the U.S. to continue its leadership role in international nuclear non-proliferation negotiations.

1.2 Role of Government Support

The previous section outlined the four major benefits of nuclear power: increasing diversity, reliability, low emissions, and maintaining a leadership role in global nuclear security decisions. These benefits behoove federal and state governments to have a role in supporting and encouraging investment in the nuclear industry. Specifically, it is recommended that:

- From an economic perspective, federal and state governments should create policies to correct any distortions in the electricity market that may create disadvantages for nuclear power generation. More on market distortions can be found in Section 2.
- From a research perspective, federal and state governments should financially support research endeavors that will lead to better performance of the nuclear fleet. This will include research into new materials, advanced power cycles, and thermal hydraulic phenomena.
- From a social perspective, federal and state governments should pursue outreach programs to highlight the benefits of nuclear power and correct any misperceptions of the technology.

1.3 Format of Report

Section 1 introduced four value propositions for nuclear power and provided an argument for the government to play a role in the nuclear industry. Section 2 summarizes the current status of nuclear power in the U.S. It includes a description of the electricity market and why the failures of the market is leading to premature closing of nuclear power plants. Section 3 compares the characteristics of nuclear power to other electricity generating sources. It explains the characteristics that nuclear power will need if it is to be competitive in the current market.

Section 4 analyzes the historical component and system breakdown of LWR costs and their impact on the overall cost of nuclear power. Conclusions are drawn from the different published costs. Section 5 examines the costs of commodities and equipment and evaluates the impact of installation rate of concrete and steel on the overall cost of each commodity. Section 6 established the concept of the first-of-a-kind (FOAK) premium and how this premium is affected by reactor size and learning rate.

Finally, Section 7 summarizes three identified opportunities to support further research on cost reduction possibilities. Section 8 provides concluding remarks from the study.

Appendix A summarizes the current U.S. electricity market. Appendix B provides a review of electricity market economic terms with definitions and examples.

2. CURRENT STATUS OF NUCLEAR POWER PLANTS IN THE U.S.

In the U.S., nuclear power provided about 20% of the electricity generated (EIA 2017b). There are 99 operating nuclear reactors and two under construction at the Vogtle site. Construction of two additional reactors at the VC Summer site has been halted (World Nuclear Association 2017b).

2.1 Current Electricity Market Conditions

Electricity markets have two important economic features. First, the output (electricity) cannot currently be stored in a cost-effective way. Because of this, supply must equal demand at all times. A second feature is that demand is constantly varying at all times and is not perfectly predictable. While daily, weekly, and seasonal trends can be predicted, there are elements of demand which are random, such as the effect of weather (for example, heat causing an increased load from air conditioning units) or random demand fluctuations.

To handle the requirement for supply to meet demand at all times, there must be enough electricity generators on the grid to handle the peak load. In addition, as a safety margin, grids build in additional reserve capacity. The reserve capacity margin is typically 15% of expected peak demand. In order to handle a fluctuating demand, there must be generators on the grid that can ramp up and down in power quickly. In addition, there must be power plants that can continually run to provide base load electricity, which is the constant load that is made up of continuous use applications (such as refrigerators or some industrial applications).

The U.S. has three main electricity grids: Electric Reliability Council of Texas, the Eastern Interconnection, and the Western Interconnection. There are two main market structures for selling electricity on the grid: regulated/public power and competitive. In a regulated market, utilities are guaranteed a rate of return for generating electricity. In a competitive market, power plants bid into the market. The demand is met by aggregating the lowest bids. The highest bid that is accepted is the price that is paid to all power plants with accepted bids. For more information on the electricity market in the U.S., see Appendix A.

Wholesale electricity prices have declined over the past decade, as shown in Figure 6. There are several drivers for this decline (Davis and Hausman 2016):

- Decrease in the price of natural gas due to increased availability and technology advancement
- Rise in capacity of renewables
- Relatively stagnant electricity demand.

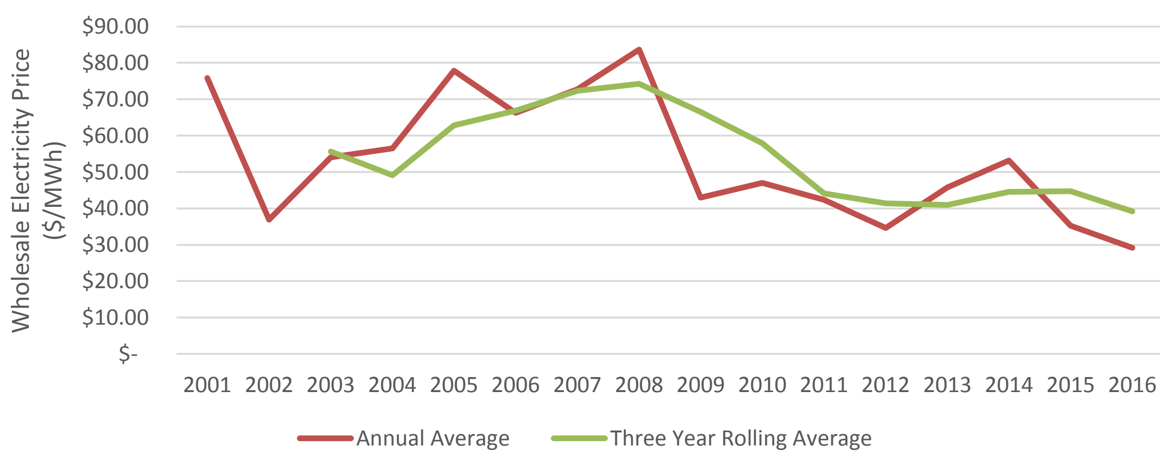


Figure 6. Average wholesale electricity price in the U.S. (2015 dollars) data from (EIA 2017c).

The decision to install new power plants as well as retire existing power plants is conducted differently in the different market types. In a regulated market, the decision is made through an arrangement between the power plant owner and the economic regulator. The regulator will review all major decisions, including major capital expenditures. If it is projected that the continuing operation of the power plant will result in higher electricity rates for the customers as compared to the options available by retiring the plant, then the regulator and power plant owner will decide to retire the plant, even if it is before the end of the plant's license. In a public power utility, the decision-making procedure is similar to that of a regulated market. However, it is simpler because the economic regulator is also the owner of the power plant. In a competitive market, the power plant owner does not have responsibility for replacing the capacity taken offline if a power plant is closed. Therefore, the cost of replacing capacity is not a factor in the decision to retire a plant early. Rather, the decision is made based on short-term cash flows, which depends on the commodity electricity market. If the difference between the revenue and the power plant generating cost (including all O&M, capital expenses, and fuel) is negative, then the plant has negative cash flows and is not making a profit and could potentially retire.

This highlights a discrepancy between the electricity markets. The same power plant that may close in a competitive market may not close in a regulated electricity market. The economic decisions made in a regulated market include a wider range of benefits from a power plant, such as jobs, environmental impact, reliability, and fuel diversity. These benefits are not reflected in the electricity commodity price and so competitive market power plants do not receive compensation for these benefits. In addition, regulated market power plant owners must consider the cost of replacing the power plant, whereas this cost does not factor into decisions made by competitive market power plant owners.

2.2 Premature Closing of Nuclear Power Plants

Since the wholesale electricity price is declining while the operating cost of the nuclear power plants is remaining relatively constant, many plants have recently become unprofitable, as seen in Figure 7.

Figure 7. Comparison of wholesale electricity price and fuel, capital, and operating cost of nuclear power plants in the U.S. (2015 dollars) (EIA 2017c, Nuclear Energy Institute 2016).

There is an increase in the generating cost of nuclear power plants until 2012. This increase has several explanations (Davis and Hausman 2016):

1. Rising labor costs (increase by 21.5% in real terms between 2002 and 2013)
2. New safety requirements as a result of the Fukushima Daiichi accident
3. Aging of reactors.

After 2008, the difference between the price received and cost incurred for an MWh declined sharply. In 2012 and 2015, the revenue generated was less than the cost of producing an MWh, which indicates average negative profits across the nuclear fleet for those years.

2.2.1 Announced Nuclear Power Plant Premature Closures

Since 2013, there have been five nuclear power plants (six reactors) prematurely[d] closed in the U.S. In addition, six nuclear power plants (eight reactors) have announced intentions to prematurely close. The most common reasons cited by the operating company for a nuclear power plant premature closure is low wholesale electricity prices and high operating cost. In addition, a large capital expense can cause a plant to prematurely close.

There are three nuclear power plants (four reactors) in the past 5 years that have announced the intention to prematurely close; however, the decision was reversed after policy action by the state government. These are summarized in Table 3.

Table 1 summarizes nuclear power plants that have prematurely closed in the past five years. Table 2 summarizes nuclear power plants that have announced the intention to prematurely close.

The most common reasons cited by the operating company for a nuclear power plant premature closure is low wholesale electricity prices and high operating cost. In addition, a large capital expense can cause a plant to prematurely close.

There are three nuclear power plants (four reactors) in the past 5 years that have announced the intention to prematurely close; however, the decision was reversed after policy action by the state government. These are summarized in Table 3.

Table 1. Premature closing of U.S. nuclear power plants.

Nuclear Reactor	Location	Commercial Operation	Closure	Rated Power	Market Type	Reason for Closure
San Onofre 2	San Clemente, California	1983	2013	1,127 MWe	Regulated	Steam generator replacement cost[a]
San Onofre 3	San Clemente, California	1984	2013	1,127 MWe	Regulated	Steam generator replacement cost[a]
Kewaunee	Carlton, Wisconsin	1974	2013	556 MWe	Competitive	Power Purchase Agreement (PPA) expiration and low wholesale electricity prices[b]
Crystal River 3	Crystal River, Florida	1977	2013	860 MWe	Regulated	FOAK repair to containment cost[c]
Vermont Yankee	Vernon, Vermont	1972	2014	620 MWe	Regulated	Low wholesale electricity prices[d]
Fort Calhoun	Fort Calhoun, Nebraska	1973	2016	476 MWe	Public Power Utility	Low wholesale electricity prices and high operating cost[e]

[a]Edison International 2013
[b]Dominion Energy 2012
[c]Duke Energy 2017
[d]Entergy 2013
[e]Epley 2016

[d] Premature closure is defined here as before the end of the operating license expiration.

Table 2. Announced premature closing of U.S. nuclear power plants.

Nuclear Reactor	Location	Commercial Operation	Expected Closure	Rated Power	Market Type	Reason for Closure
Palisades	Covert, Michigan	1971	2018	800 MWe	Competitive	PPA early termination agreement[a]
Three Mile Island 1	Middleton, Pennsylvania	1974	2019	819 MWe	Competitive	Low Wholesale electricity prices and high operating cost[b]
Oyster Creek	Forked River, New Jersey	1969	2019	636 MWe	Competitive	Cooling tower addition cost[c]
Pilgrim	Plymouth, Massachusetts	1972	2019	685 MWe	Competitive	Low wholesale electricity prices and high operating cost[d]
Indian Point 2	Buchanan, New York	1974	2020	1,032 MWe	Competitive	Low wholesale electricity prices and high operating cost[e]
Indian Point 3	Buchanan, New York	1976	2021	1,051 MWe	Competitive	Low wholesale electricity prices and high operating cost[e]
Diablo Canyon 1	Avila Beach, California	1985	2024	1,118 MWe	Regulated	Agreement to replace capacity with renewables[f]
Diablo Canyon 2	Avila Beach, California	1986	2025	1,122 MWe	Regulated	Agreement to replace capacity with renewables[f]

[a]Parker 2016
[b]Exelon 2017
[c]Wald 2010
[d]Entergy Newsroom 2015
[e]Entergy Newsroom 2017
[f]PG&E News Releases 2016

Table 3. State policies enabling the reversal of announced premature nuclear power plant closure decisions.

Nuclear Reactor	Location	Commercial Operation	Rated Power	Market Type	Reason for Closure	Reason for Decision Reversal
Fitzpatrick	Scriba, New York	1975	838 MWe	Competitive	Low Wholesale Electricity Prices and High Operating Cost[a]	Sale of plant to Exelon and enactment of New York State's Clean Energy Standard Program[b]
Clinton	Clinton, Illinois	1984	1,098 MWe	Competitive	Negative Profit[c]	Passage of Future Energy Jobs Bill in Illinois establishing Zero Emission Credits[d]
Quad Cities 1	Cordova, Illinois	1973	940 Mwe	Competitive	Negative Profit[c]	Passage of Future Energy Jobs Bill in Illinois establishing Zero Emission Credits[d]
Quad Cities 2	Cordova, Illinois	1973	940 Mwe	Competitive	Negative Profit[c]	Passage of Future Energy Jobs Bill in Illinois establishing Zero Emission Credits[d]

[a]Entergy Newsroom 2015
[b]Entergy Newsroom 2017
[c]Exelon Newsroom 2016
[d]Illinois Power Agency 2017

2.2.2 Effect of Nuclear Power Plant Closures

If a nuclear power plant is prematurely closed, then electricity prices could increase if the replacement cost is higher than the going forward cost of the nuclear power plant. This was seen in California following the closing of the San Onofre Nuclear Power Plant in 2013. Davis and Hausman (2016) show that other generating units experienced a total increased generation cost of $350 million during the year following the closure (Makovich et al. 2014).

Haratyk (2017) shows that there are currently 18.5 GW unprofitable nuclear power plants currently in the U.S. (6.5 GW of which are the announced retirements shown in Table 2). If these plants were to close and were replaced by natural gas, the carbon emissions from the power sector would increase by 3.2%. If the plants were instead replaced by non-carbon emitting wind, the cost to the federal tax credit and renewable portfolio standard program would be more than $5 billion per year (Haratyk 2017).

2.3 Uncertainty in Future Market Conditions for Nuclear Power

Uncertainty in future profits creates a risk for companies either considering investing in new nuclear power units or maintaining current nuclear power units. Profit is defined as the difference between revenue earned and costs incurred. There is uncertainty in both future revenue as well as future costs.

Uncertainty in revenue comes from imperfectly predicting electricity wholesale prices. Aside from the short-term fluctuations in wholesale electricity price, long–term uncertainty exists. This is caused by many factors, including unknown future renewable penetration as well as unknown future emission policies. Uncertainty in costs comes from unknown future capital expenditures. The need for such expense can come from either maintenance/aging or from regulatory requirements (World Nuclear Association 2017a).

3. NECESSARY ATTRIBUTES FOR NUCLEAR POWER TO BE SUCCESSFUL

Aside from the technologically unique aspect of nuclear power, such as radiation and prolonged radioactive waste, nuclear power has economic attributes that differentiates it from the economic aspects of other power generation technologies.

3.1 Comparison of Nuclear Power Characteristics to Other Generation Sources

Nuclear power plants typically experience initial high capital cost during construction. After construction, they have a fixed operation and maintenance (O&M) cost similar to that of coal but with a lower fuel cost. Figure 8 shows the relative contribution of different cost areas to the levelized cost of electricity[e] (LCOE) of coal, natural gas, nuclear, wind, photovoltaic (PV) solar, and concentrating solar power (CSP) with a 12-hour storage capability. Data are from the Nuclear Energy Agency (NEA) (Wittenstein and Rothwell 2015). As can be seen, the fuel and O&M cost for nuclear only comprises 22% of the total cost over the lifetime of the unit. Instead, the capital cost dominates the overall LCOE. However, it is important to note that profit is not determined by LCOE. As stated in the previous section, the ability to profit in a marketplace will depend on the operating costs and revenue.

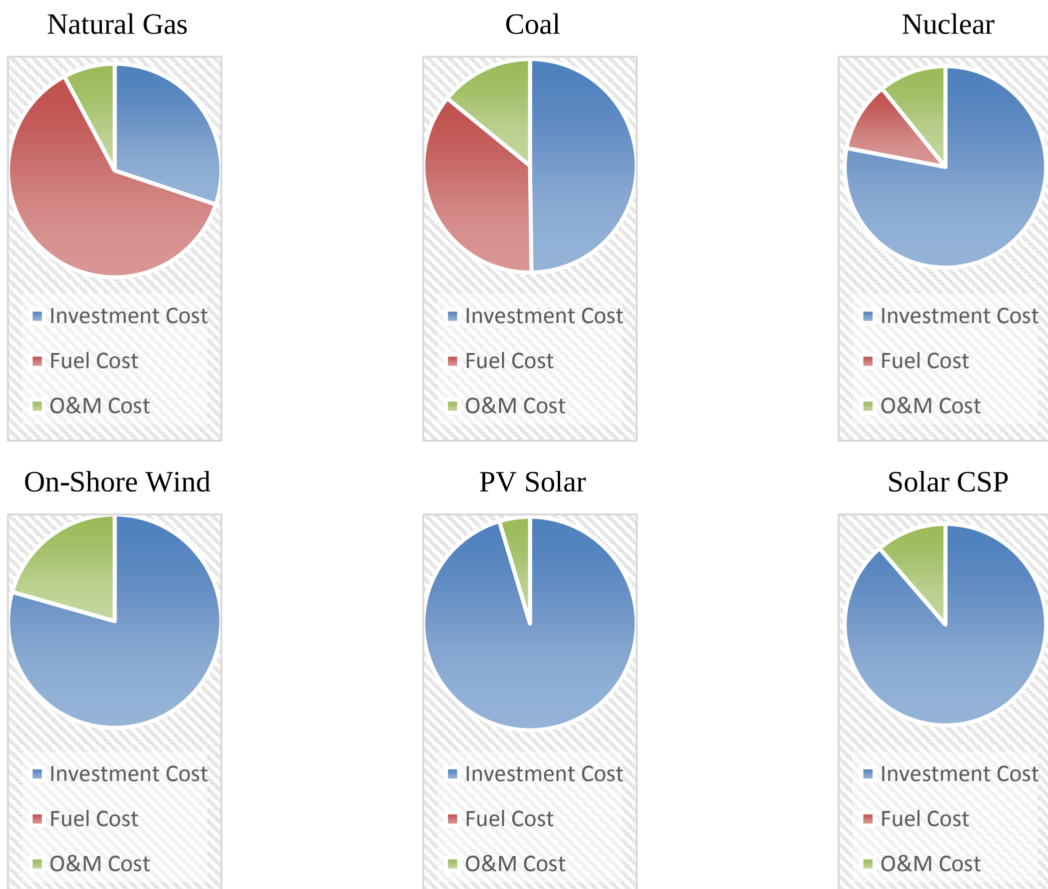


Figure 8. Percent contribution to LCOE of cost categories for coal, natural gas, nuclear, wind, PV solar, and solar CSP. Data from (Wittenstein and Rothwell 2015).

[e] LCOE is used for comparison between different electricity generation technologies with different lifetimes. Costs to the plant are discounted to the initial year of commercial operation of the plant. See Appendix B for detailed information on calculating LCOE.

Figure 9 shows how the upfront cost of building a power generation unit (including capital, financing, etc.) compares to the ongoing cost of operating a power generation unit (including fuel, fixed and variable O&M, etc.) for coal, natural gas, nuclear, wind, PV solar, and solar CSP. The data is from NEA (Wittenstein and Rothwell 2015). The line represents a 1:1 ratio between these costs. Being on the line, coal's costs are split evenly. Natural gas has a lower upfront cost than ongoing cost. Nuclear, onshore wind, solar CSP, and PV solar have higher upfront costs than ongoing costs.

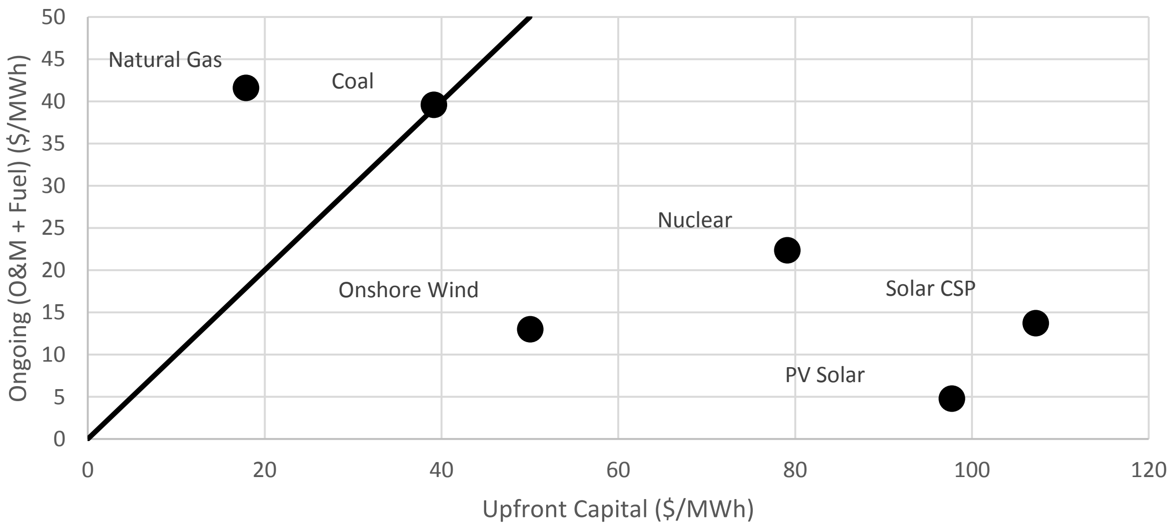


Figure 9. Comparison of levelized upfront costs and ongoing cost for coal, natural gas, nuclear, wind, and solar. Data from (Wittenstein and Rothwell 2015).

3.2 Current Nuclear Power Construction Cost Breakdown

Construction costs dominate the LCOE of nuclear power plants. Construction costs can be broken down into four main categories:

- Owner's cost: the cost of land and any other applicable finance cost (such as taxes)
- Contingency cost: an allowance for budget margin
- Direct cost: the cost of equipment, structures, material, and installation labor
- Indirect cost: the cost of designing, engineering, and managing the construction.

Note that the combination of direct cost and indirect cost make up the overnight cost. Figure 10 shows the theoretical capital cost breakdown of a two-unit AP1000 power plant. The direct cost is subdivided into three categories: civil structural material and installation, mechanical equipment supply and installation, and electrical I&C supply and installation. Costs are from (EIA 2016).

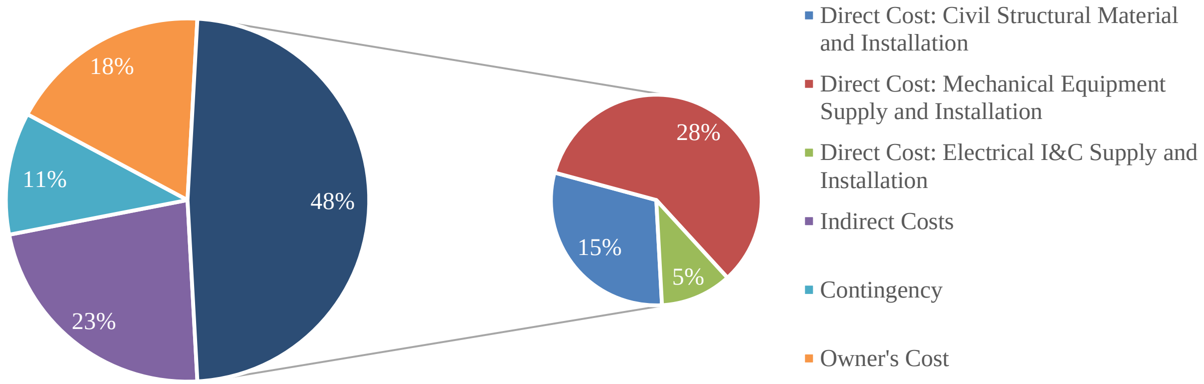


Figure 10. Theoretical cost breakdown of two-unit AP1000 construction project in the United States (EIA 2016).

NEA provides an estimated cost breakdown of twin advanced boiling water reactor (ABWR) reactors each with a capacity of 1,400 MWe (NEA 2000). The direct cost breakdown is shown in Figure 11. The indirect cost breakdown is shown in Figure 12.

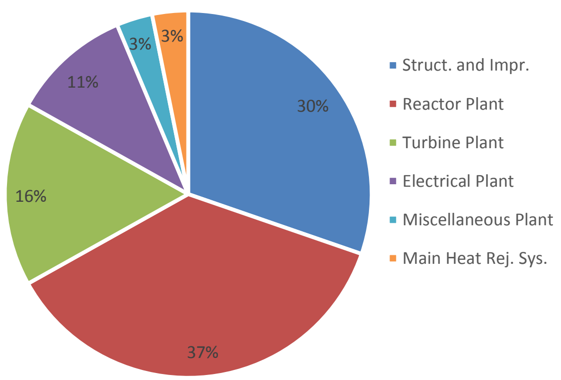


Figure 11. Theoretical breakdown of ABWR direct costs (NEA 2000).

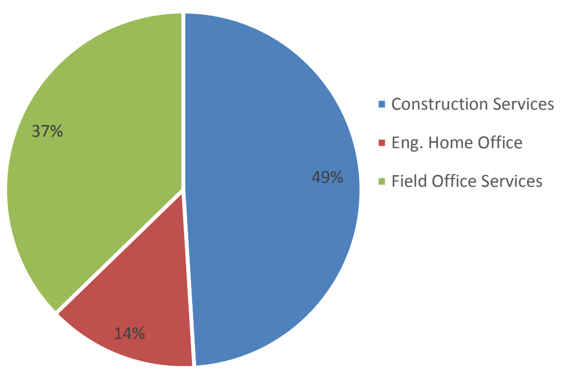


Figure 12. Theoretical breakdown of ABWR indirect costs (NEA 2000).

Direct cost makes up about half of the cost of the construction. Much of this is the labor and construction itself rather than the components. This is also true in the indirect cost breakdown, where construction services constitute about half of the indirect cost (NEA 2000).

3.3 Necessary Attributes for Success in Current Electricity Market

The electricity market was described in Section 2 as a system that currently does not compensate some of the characteristics of the generation source (such as low carbon emitting, reliability, etc.). To be profitable in the current electricity market, nuclear power plants need to have the characteristics that are valued. Two criteria are essential to being profitable in the current electricity market: (1) the capital cost and risk of building new generation must be reasonable enough to attract investment and (2) the O&M cost (both fixed and variable) must be below the average wholesale price of electricity.

The construction cost of a nuclear power plant is high relative to alternatives such as the construction cost of a combined cycle natural gas plant. NEA gives estimates for the overnight cost of an nth-of-a-kind (NOAK) nuclear power plant in the United States to be $4,100/kWe (Wittenstein and Rothwell 2015). For a 1,000 MW unit, the total cost would be $4,100,000,000. Utilities will need to either take out loans or attract investors to finance the construction of a reactor. The total cost of the nuclear power plant must be low enough to attract these investors.

Nuclear projects must have as low investment risk as possible. The higher the risk of a project, the higher the risk premium that investors will apply to their financing, which will increase the cost of financing. The utility constructing the reactor will need to have a strong balance sheet, established cash flow, and preferably have experience in building and operating a nuclear fleet. Projects in regulated electricity markets are less risky than in competitive electricity markets because the regulated markets offer a guaranteed rate of return through regulated ratemaking (World Nuclear Association 2017a).

Risk premiums also have a multiplication effect on cost overruns during construction if there is a delay. The longer the time that an amount of money is borrowed, the more interest that is charged on it. In addition, if the delay and cost overruns cause the project to need to get further investments, there will be a higher risk premium than the original one because the project is riskier. Therefore, cost overruns must be avoided. Further, if the nuclear industry has a poor track record of constructing and operating nuclear power plants, then there will be a higher risk premium regardless of the company building the new plant (World Nuclear Association 2017a).

For a nuclear power plant to be profitable in an electricity market, its O&M cost (fixed and variable) must be below the average wholesale price of electricity. In addition, the nuclear power plant must have enough positive cash flow to pay off construction capital and allow for any new large capital expenditures or repairs. Variable electricity generation cost is dominated by the fuel cost. Nuclear fuel costs comprise mining, enrichment, manufacturing, and waste management. A large part of fixed O&M costs is the labor and support required at the power plant. Some of this is mandated by the NRC, such as security which make up 5% of fixed O&M cost (Haratyk 2017). Nuclear power plants could reduce costs by reducing staff size, while maintaining the same level of safety and reliability.

The attributes that a nuclear power plant must have to be profitable in the electricity market are:

- Reasonable capital cost for investment
- Minimum capital investment risk (predictable rate of return)
- Limited overruns or delays during construction
- Low fuel cost
- Low fixed O&M cost.

4. MAJOR COST COMPONENTS OF LWR CONSTRUCTION

This section examines the cost breakdown of light water reactors. An extensive literature review was performed and cost breakdowns from five reports are summarized here. One must take care in comparing two reported nuclear construction cost values from different sources. This is because, as described in (Du and Parsons 2009), each cost reporting consists of different assumptions and exclusions. For example, some of the reported cost breakdowns include pre-construction costs while other cost breakdowns assume construction at a pre-existing site. Therefore, each of the reported cost breakdowns will be summarized individually.

4.1 WASH 1230 (1971)

The U.S. Atomic Energy Commission published the WASH 1230 report series with the purpose of providing a detailed cost investment study of nuclear power plants, coal-fired power plants, and oil-fired power plants. The cost breakdown presented in this section is from the first volume of the report series, which reports the cost breakdown for a typical 1,000 MWe pressurized water reactor (PWR) unit (United Engineers and Constructors, Inc. 1972). No adjustments were made to the magnitude of the costs from the 1971 reported dollar amounts.

The cost estimates were generated based upon experience constructing PWR reactors. It was assumed that there was no restriction on cooling water intake and that the plant was cooled using river water that is directly discharged back into the river. There is no cooling tower. More information on the site design and assumptions can be found in the original report (United Engineers and Constructors, Inc. 1972). The cost breakdown is shown in Figure 13. A description of the cost breakdown categories is summarized in Table 4.

The turbine equipment category is the largest cost category. The turbine generator equipment composes a little over half of this cost. However, these numbers have not been adjusted since 1971. It is expected that the cost of the turbine generator has decreased in the 45 years since this report due to technological and manufacturing advances. The reactor plant equipment category is the second highest cost category. About half of this cost is the reactor coolant system and about a quarter of this cost is the reactor pressure vessel. Undistributed costs and structures and improvements cost categories each make up about a fifth of the total cost. The electric plant equipment and miscellaneous plant equipment are not significant cost contributors. The ratio between the equipment cost categories and the structures and improvements category is 7:2.

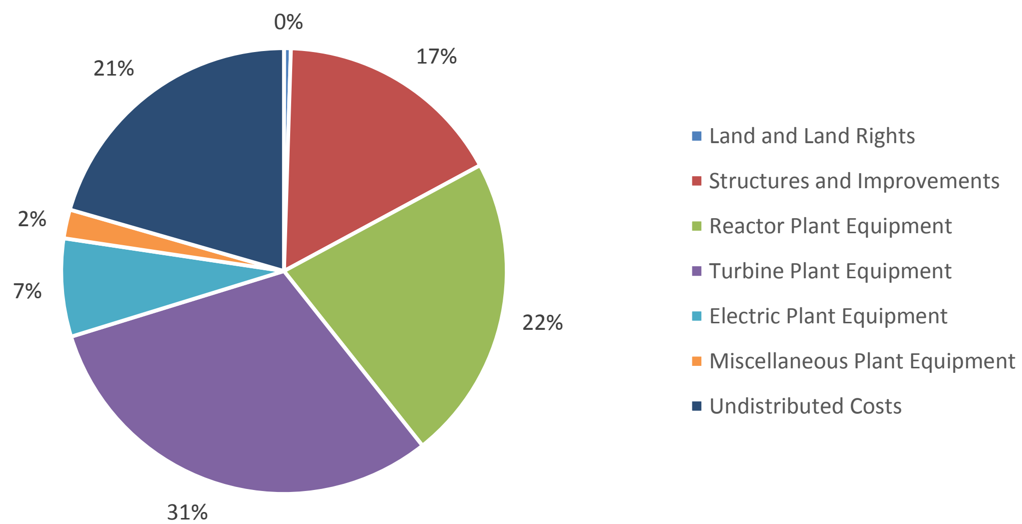


Figure 13. Cost breakdown for a typical 1,000 MW PWR unit.

Table 4. Description of cost breakdown categories for Figure 13.

Category	Description
Land and Land Rights	Purchasing, surveying, and clearing land
Structures and Improvements	Civil work and civil structures (mostly buildings, including reactor and turbine buildings)
Reactor Plant Equipment	Equipment needed for reactor (reactor pressure vessel, coolant system, etc.)
Turbine Plant Equipment	Equipment needed for steam turbine (steam turbine, feedwater heating system, etc.)
Electric Plant Equipment	Equipment needed for electricity (switchgear, cabling, etc.)
Miscellaneous Plant Equipment	Items not included in above categories
Undistributed Costs	Support services and facilities (professional and construction services, construction facilities, etc.)

4.2 Reduction of Capital Costs of Nuclear Power Plants (2000)

The *Reduction of Capital Costs of Nuclear Power Plants*, is a report published by the Organisation for Economic Co-operation and Development NEA. The purpose of the report was to identify methods to reduce capital cost and analyze the effectiveness of those methods. It looks at different reactor designs, different reactor sizes, and different number of reactor units on a site. One of the reactors studied is the ABWR technology. It is assumed that two ABWR units are installed on a pre-existing site in the U.S. (NEA 2000). The cost breakdown is shown in Figure 14. A description of the cost breakdown categories is summarized in Table 5.

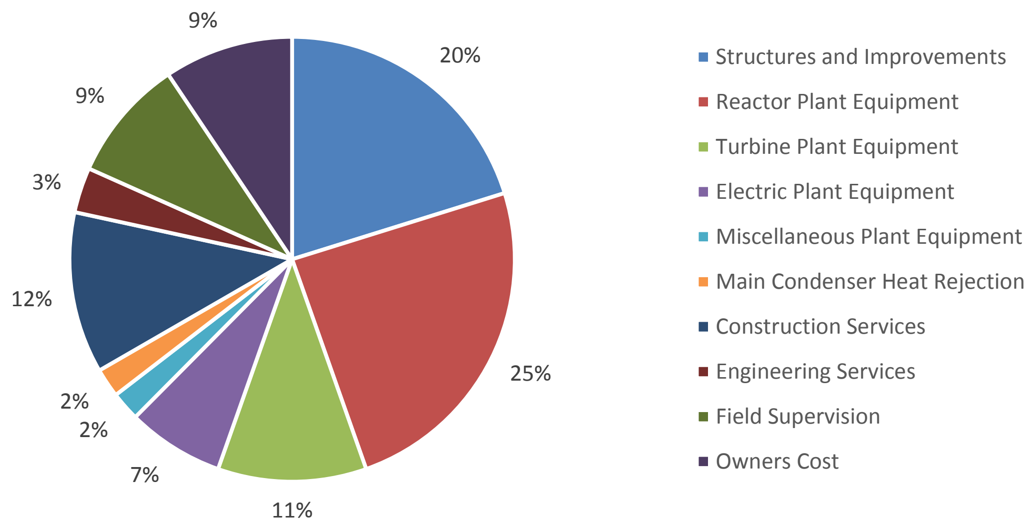


Figure 14. Overnight capital cost (excluding contingency) for an nth-of-a-kind ABWR unit.

Table 5. Description of cost breakdown categories for Figure 14.

Category	Description
Structures and Improvements	Civil work and civil structures (mostly buildings, including reactor and turbine buildings)
Reactor Plant Equipment	Equipment needed for reactor (reactor pressure vessel, coolant system, etc.)
Turbine Plant Equipment	Equipment needed for steam turbine (steam turbine, feedwater heating system, etc.)
Electric Plant Equipment	Equipment needed for electricity (switchgear, cabling, etc.)
Miscellaneous Plant Equipment	Items not included in above categories
Main Condenser Heat Rejection	Includes equipment and buildings needed for condenser hear rejection (cooling tower, piping, etc.)
Construction Services	Services needed to support construction (construction facilities, cranes, etc.)
Engineering Services	Engineering support (design engineers, managers, etc.)
Field Supervision	Direct supervision of craft-labor activities (e.g., field engineers and superintendents)

The reactor plant equipment is the largest cost category. Unfortunately, the data in this report does not go further in depth than the above cost categories so it is unknown what the largest contributor is to the reactor plant equipment. The structures and improvements are the second largest cost category followed by the construction services category. Turbine plant equipment is the fourth largest cost category. The ratio between the equipment cost categories and the structures and improvements category is 7:3.

4.3 Tennessee Valley Authority (2005)

The Tennessee Valley Authority report was done in cooperation with the U.S. Department of Energy and Toshiba Corporation, General Electric Company, U.S. Enrichment Corporation, Bechtel Power Corporation, and Global Nuclear Fuels – America. The purpose of the report was to provide a cost and schedule evaluation of the addition of two ABWR units to the Bellefonte site (Toshiba Corporation 2005). The cost breakdown is shown in Figure 15. A description of the cost breakdown categories is summarized in Table 6.

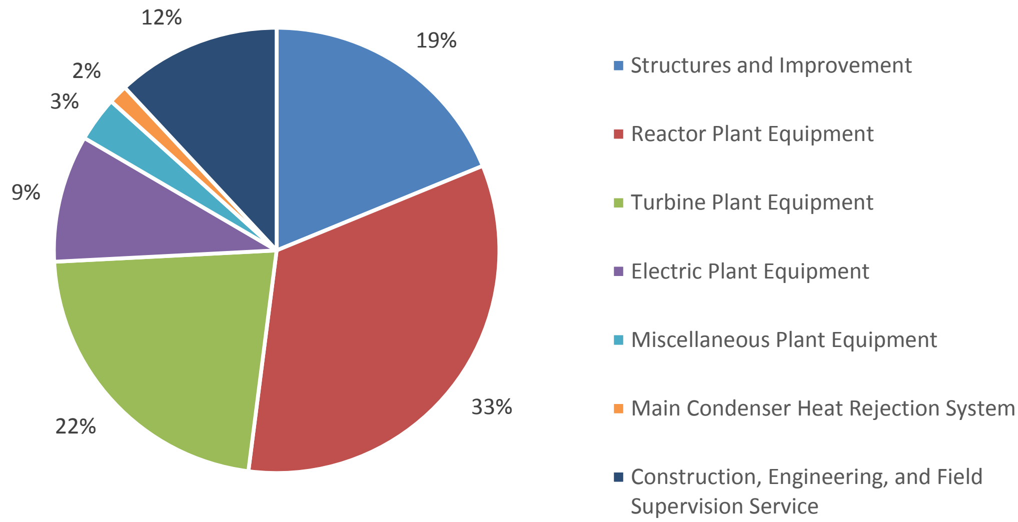


Figure 15. Cost estimate (excluding labor) for construction of two ABWR units on the existing Bellefonte Site (Toshiba Corporation 2005).

Table 6. Description of cost breakdown categories for Figure 15.

Category	Description
Structures and improvements	Civil work and civil structures (mostly buildings, including reactor and turbine buildings)
Reactor plant equipment	Equipment needed for reactor (reactor pressure vessel, coolant system, etc.)
Turbine plant equipment	Equipment needed for steam turbine (steam turbine, feedwater heating system, etc.)
Electric plant equipment	Equipment needed for electricity (switchgear, cabling, etc.)
Miscellaneous plant equipment	Items not included in above categories

The reactor plant equipment is the largest cost category, followed by the turbine plant equipment category and then the structures and improvement category. The construction, engineering, and field supervision category is the fourth largest cost category. It should be noted that these costs exclude labor, which can be as much, if not more than, the cost of the materials and equipment. The ratio between the equipment cost categories and the structures and improvements category is 7:2.

4.4 World Nuclear Supply Chain: Outlook 2030 (2014)

The World Nuclear Supply Chain Outlook report is published by the World Nuclear Association. It summarizes the status and trends as well as the market outlook for the nuclear industry. It also reports challenges for the nuclear industry. As part of the market outlook, the report provides a breakdown of a typical nuclear power plant. It is not specified which nuclear technology the plant contains or where it is constructed. The costs are stated to be an adaption of an aggregation of published sources (World Nuclear Association 2014). The cost breakdown is shown in Figure 16. A description of the cost breakdown categories is summarized in Table 7.

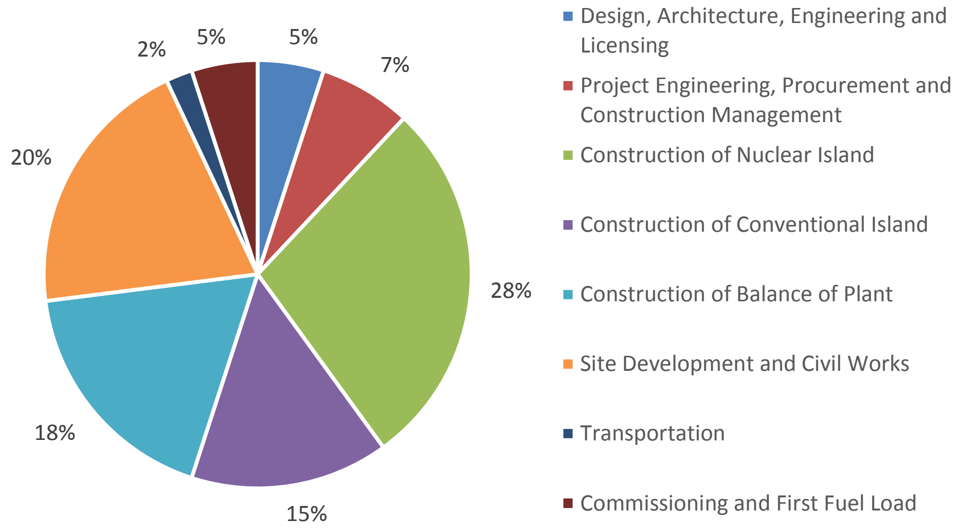


Figure 16. Typical nuclear power plant construction cost adapted from published sources (World Nuclear Association 2014).

Table 7. Description of cost breakdown categories for Figure 16.

Category	Description
Design, architecture, engineering, and licensing	Pre-construction reactor design and licensing
Project engineering, procurement, and construction management	Any necessary project management work both onsite and support offsite
Nuclear island	Construction and installation of the nuclear island
Conventional island	Construction and installation of the conventional island (e.g., turbine building)
Balance of plant	Construction and installation of the balance of plant (heat rejection system)
Site development and civil works	Construction of auxiliary and support buildings as well as roads, sidewalks, etc.
Transportation	Transportation of equipment and components to site
Commissioning and first fuel load	Cost of starting reactor, including the cost of the first fuel load

This cost breakdown is different from the previous three reports. This cost breakdown includes pre-construction costs (the design, architecture, engineering, and licensing category), which is estimated at approximately equivalent to the cost of the commissioning and first fuel load. The largest cost is the construction of the nuclear island, which in this case includes not only the equipment but also the building. The four construction categories: nuclear island, conventional island, balance of plant, and site development and civil works make up approximately 80% of the total cost reported here. The design and licensing is insubstantial compared to the construction costs.

4.5 Leidos Report (2016)

The Leidos report summarizes the performance and costs for 15 different power generation technologies, including a dual unit installation of the Westinghouse AP1000 design on a pre-existing site. It was commissioned by the EIA. The purpose of the cost and performance information is to be used as inputs into the National Energy Modeling System for the Electricity Market Module (Leidos Engineering 2016). The cost breakdown is shown in Figure 17. A description of the cost breakdown categories is summarized in Table 8.

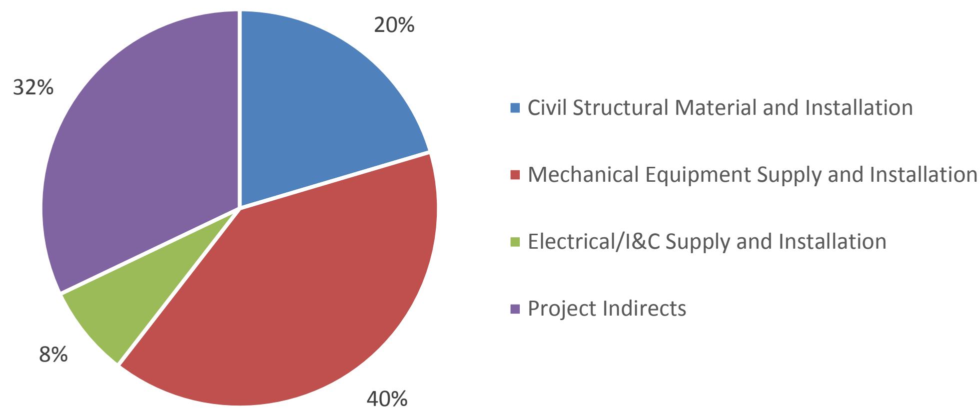


Figure 17. Capital cost estimate for two AP1000 units on a pre-existing site (Leidos Engineering 2016).

Table 8. Description of cost breakdown categories for Figure 17.

Category	Description
Civil structural material and installation	Cost of all support and auxiliary buildings as well as roads, sidewalks, etc.
Mechanical equipment supply and installation	Cost of nuclear reactor, necessary cooling system, and steam turbine and all necessary support systems and equipment
Electrical/instrumentation and controls supply and installation	Cost of electric generator and necessary support systems and equipment
Project indirects	Includes any engineering, construction management, and support facilities as well as start-up costs

Only four cost categories are reported here. The mechanical equipment installation has the highest cost category, followed by the indirect costs. The civil cost category is the third highest. The electrical equipment cost category does not represent a significant cost. The ratio between the equipment cost categories and the structures and improvements category is 7:3.

4.6 Overall Cost Breakdown Conclusions

It is hard to compare percentage cost breakdowns from different reports unless all of the cost accounting is done using the same method and using the same assumptions. However, we can draw conclusions from looking at each of these cost reports.

The ratio between combined equipment costs (reactor, turbine, electrical, and miscellaneous) and structures and improvements is fairly consistent between the reports at between 7:2 and 7:3. This ratio cannot be calculated for the World Nuclear Supply Chain report because the costs are not broken down between equipment and buildings. This indicates that the purchase and installation[f] (both materials and labor) of the equipment is about 2–4 times the cost of constructing the buildings. In addition, it is seen that when indirect costs are reported, they represent a significant portion of the cost. When pre-construction costs are reported, they do not represent a significant portion of the total cost.

[f] Excluding construction supervision, engineering, and construction management costs associated with installation, which are reported separately.

5. COMMODITY AND EQUIPMENT COST DRIVERS

A large portion of construction cost of a nuclear power plant is the cost of commodities and equipment. This cost includes both the cost of purchasing the materials as well as the cost of installation. This section explores the costs of two commodities: concrete and steel. A parameterization is performed on the man hours required to install concrete and steel. The additional “nuclear premium” for steel and concrete is also quantified. The section then examines how the cost of a steam turbine, reactor coolant pumps, and steam generators scale with reactor rated power.

5.1 Commodity Requirements

Reactors require many different types of material. Figure 18 shows the breakdown of materials in a typical PWR by weight.

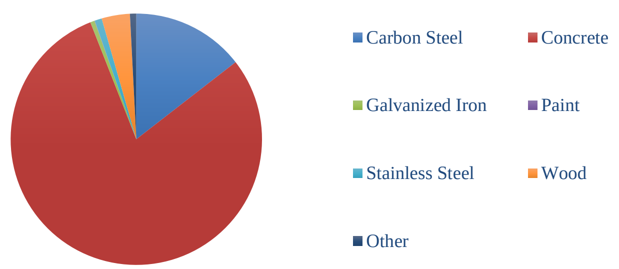


Figure 18. Material composition of a typical PWR by weight (Bryan and Dudley 1974).

Concrete represents about three quarters of the total material used. Carbon steel is the second most abundant material at about one eighth of the total material usage. Table 9 below summarizes the total usage for each material (Bryan and Dudley 1974).

Table 9. Material usage in a typical PWR (Bryan and Dudley 1974).

Material	Nuclear Island	Balance of Plant	Entire Plant
Aluminum	6 MT (0.004%)	13 MT (0.01%)	18 MT (0.008%)
Babbitt metal	negligible	0.4 MT (0.0004%)	0.4 MT (0.0002%)
Brass	1 MT (0.001%)	9 MT (0.009%)	10 MT (0.004%)
Bronze	0.6 MT (0.0005%)	24 MT (0.02%)	25 MT (0.01%)
Carbon steel	13,364 MT (10.7%)	19,367 MT (19.2%)	32,731 MT (14.5%)
Concrete	104,885 MT (84.0%)	74,796 MT (74.1%)	179,681 MT (79.5%)
Copper	71 MT (0.06%)	624 MT (0.62%)	694 MT (0.31%)
Galvanized iron	531 MT (0.43%)	727 MT (0.72%)	1,257 MT (0.56%)
Inconel	124 MT (0.10%)	negligible	124 MT (0.06%)
Insulation	210 MT (0.17%)	712 MT (0.70%)	922 MT (0.41%)
Lead	21 MT (0.02%)	26 MT (0.03%)	46 MT (0.02%)
Nickel	negligible	0.6 MT (0.001%)	0.7 MT (0.0003%)
Paint*	46 MT (0.04%)	33 MT (0.03%)	79 MT (0.04%)
Silver	0.1 MT (0.00005%)	0.5 MT (0.0005%)	0.5 MT (0.0002%)
Stainless steel	1182 MT (0.95%)	898 MT (0.89%)	2,080 MT (0.92%)
Silver, indium, and cadmium	3 MT (0.003%)	negligible	3 MT (0.001%)
Wood	4,445 MT (3.6%)	3,764 MT (3.7%)	8,208 MT (3.6%)

*Assumes a specific gravity for paint of 1.2. Note the error in reference (Bryan and Dudley 1974) where volume of paint is reported in m^3 when the numbers reflect gallons.

The cost of a commodity in a nuclear power plant is the cost of obtaining the commodity plus the cost of installing the commodity. This is shown in Equation 1.

$$Cost = Amount \times Price + Amount \times Installation\ Rate \times Wage \qquad [1]$$

The prices for commodities depend upon market conditions, which can sometimes be volatile. The commodity costs for concrete and structural steel are in Table 10 (EMWG 2007). These commodity prices are from 2007 and have not been adjusted for any escalation on price or inflation.

Table 10. Commodity prices of concrete and structural steel (EMWG 2007).

	Nuclear	**Non-Nuclear**
Concrete[a]	$421.00/m^3	$281.43/m^3
Structural steel	$4,446.70/MT	$2,008.07/MT

[a]Concrete price was determined based on the prices for reinforcing steel, formwork, and concrete assuming an average of 0.65 m^2 of formwork for a m^3 of concrete and an average of 0.15 MT of reinforcing steel in a m^3 of concrete. These assumptions are based on the reported area of formwork, weight of reinforcing steel, and volume of concrete in the PWR Wash 1230 Report (United Engineers and Constructors 1972).

The wage for labor of a commodity depends on the commodity itself and what types of craft labor are required. Table 11 and Table 12 show the composite wages for concrete and steel (EMWG 2007). These wages are from 2007 and have not been adjusted for inflation.

Table 11. Composite wage for concrete (EMWG 2007).

Craft	Wage Rate	Percent	Contribution
Carpenter	$39.98/hr	40%	$15.99/hr
Iron worker	$45.28/hr	20%	$9.06/hr
Laborer	$31.34/hr	30%	$9.40/hr
Operating engineer	$43.24/hr	5%	$2.16/hr
Other	$38.34/hr	5%	$1.92/hr
TOTAL		100%	$38.53/hr

Table 12. Composite wage for steel (EMWG 2007).

Craft	Wage Rate	Percent	Contribution
Carpenter	$39.98/hr	5%	$2.00/hr
Iron worker	$45.28/hr	75%	$33.96/hr
Laborer	$31.34/hr	5%	$1.57/hr
Operating engineer	$43.24/hr	15%	$6.49/hr
TOTAL		100%	$44.02/hr

The installation time depends on the commodity and where it is located in the plant. For example, the installation time for commodities is higher in the nuclear island compared to that for the balance of plant. In addition, the installation time for concrete is higher for superstructures as compared to substructures. The installation times for concrete and structural steel is found in (EMWG 2007). The time is reported in required man hours per unit of commodity.

Table 13. Installation rates for concrete and structural steel (EMWG 2007).

	Nuclear	Non-Nuclear
Concrete (substructure)[a]	11.45 hr/m^3	5.59 hr/m^3
Concrete (superstructure)[a]	18.51 hr/m^3	13.88 hr/m^3
Structural steel	58.06 hr/MT	13.06 hr/MT

[a]Concrete price was determined based on the prices for reinforcing steel, formwork, and concrete assuming an average of 0.65 m^2 of formwork for a m^3 of concrete and an average of 0.15 MT of reinforcing steel in a m^3 of concrete. These assumptions are based on the reported area of formwork, weight of reinforcing steel, and volume of concrete in the PWR Wash 1230 Report (United Engineers and Constructors 1972).

5.1.1 Concrete Analysis

Concrete is the most abundant commodity in a nuclear power plant. The specific amount of concrete as well as the location of where it is being utilized differs based on reactor design. Figure 19 shows the concrete location breakdown for a typical U.S. 1970s PWR, the ABWR, the Economic Simplified Boiling Water Reactor, and the EPR reactor designs (Peterson et al. 2005).

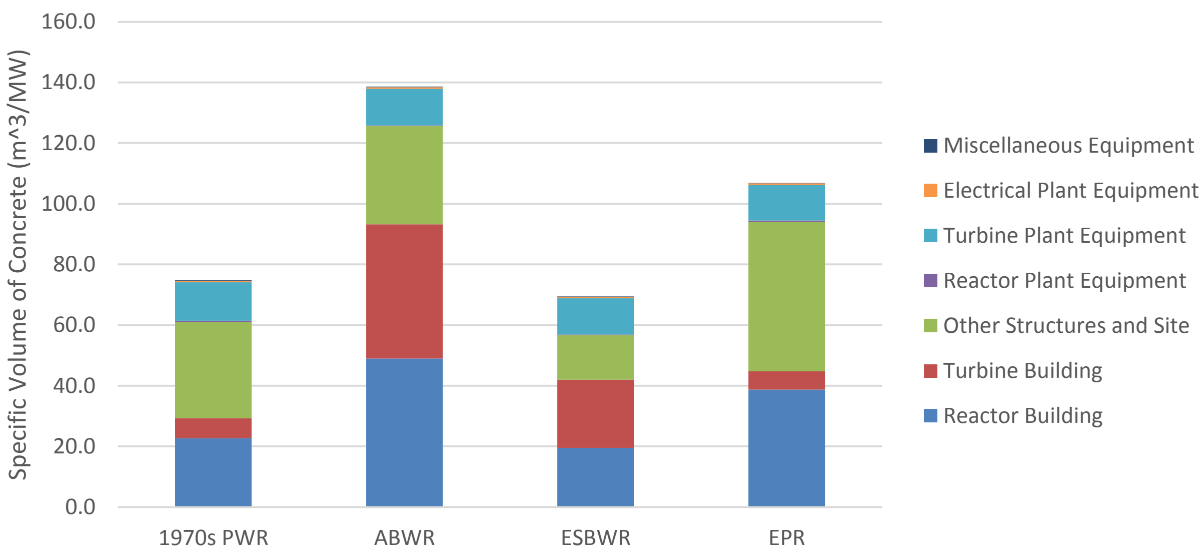


Figure 19. Concrete usage in four different reactor designs (Peterson et al. 2005).

Using the concrete commodity costs, labor rates, and composite labor wages from (EMWG 2007) as detailed in Table 10, Table 11, and Table 13 the breakdown labor and material cost of concrete was found for a typical 1,000 MWe PWR using commodity amounts from (Bryan and Dudley 1974). This is depicted in Figure 20. The total cost of concrete is estimated at $63.82/kWe.

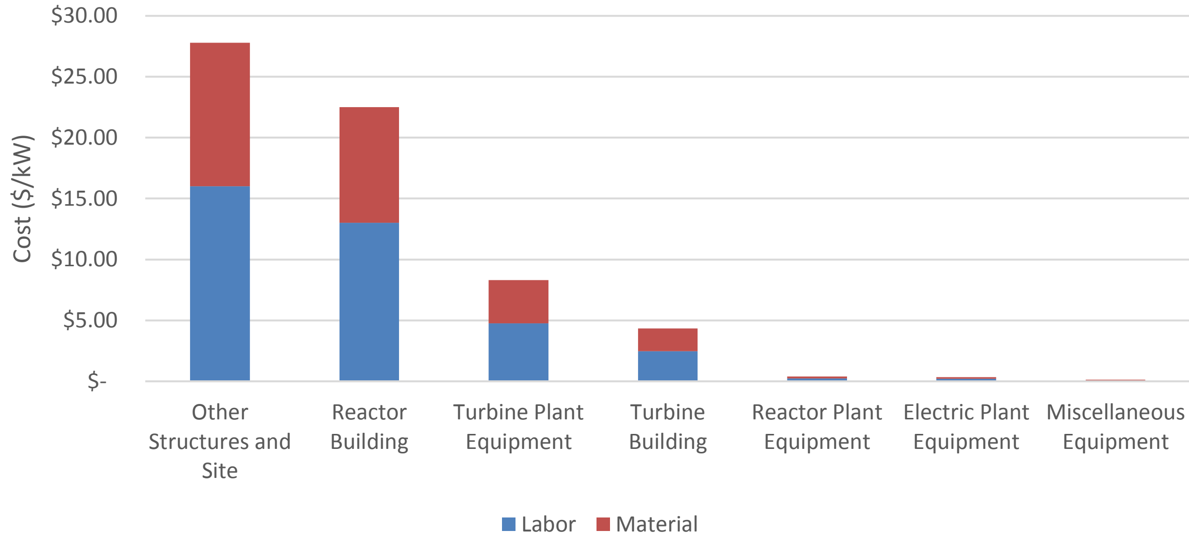


Figure 20. Concrete labor and material cost breakdown by account of a typical 1,000 MWe PWR.

The structures and site account makes up a majority of the concrete in the plant. This is because structures and site consists mainly of buildings, which require a large amount of concrete. There is little to no concrete on any of the equipment accounts, except for the turbine plant equipment account. This is due to the large turbine pedestal.

The concrete cost comprises about 58% labor costs and 42% material cost. There have been advances in decreasing the time it takes to install the concrete. Japan was able to cut the installation time of concrete in half between the 1970s and the 1980s. Toshiba states that the reasons for this include better construction equipment, larger cranes, and use of the metal decking method[g]. Additional decreases in installation time can result from use of modularization, design completion prior to construction, and prefabricated rebar (Toshiba Corporation 2005).

A parameterization is performed on the installation time of concrete. It is shown in Figure 21. The installation time is reduced down to 50% of the values in Table 13. At a 50% reduction in installation time, the estimated cost of concrete is reduced to 71% of its original value (from $63.82/kWe to $45.44/kWe).

[g] Placing piping and equipment before placing higher slabs.

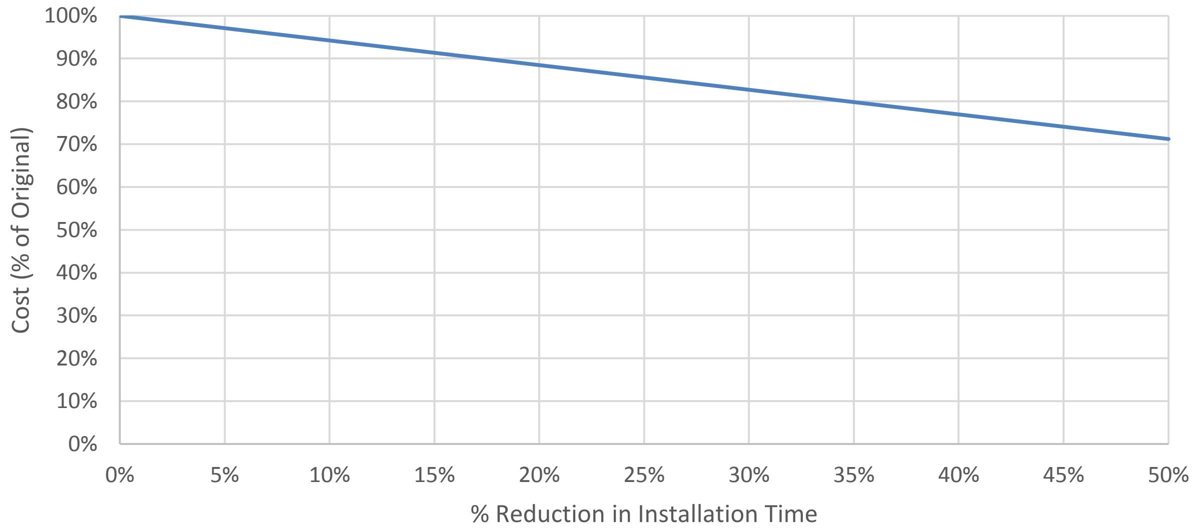


Figure 21. Concrete installation time parameterization.

This shows that a reduction of 1% in installation time of concrete results in a 0.6% reduction in total cost of concrete. Installation times for concrete can be reduced through decreasing worker idle time, increasing worker productivity, and decreasing the number of workers necessary for tasks. This is accomplished through better project management and design of the reactor with construction in mind. Another way to decrease installation times is to increase the speed of processes.

The Royal Academy of Engineering released a report in 2012 on the best practices for concrete in nuclear construction (Royal Academy of Engineering 2012). The report emphasizes the role of pre-planning in concrete installation of nuclear power plant construction projects. The pre-planning ranges from integrating concrete installation consideration in the design of the plant to ensuring technical competence of the designers and technicians. This will increase the quality of the concrete work and will result in less necessary re-work (Royal Academy of Engineering 2012).

5.1.2 Steel Analysis

Steel is the second most abundant commodity in a nuclear power plant. The specific amount of steel as well as the location of where it is being utilized differs based on reactor design. Figure 22 shows the metal (steel plus other metals) location breakdown for a typical U.S. 1970s PWR, the ABWR, the Economic Simplified Boiling Water Reactor, and the European Pressurized Reactor designs (Peterson et al. 2005).

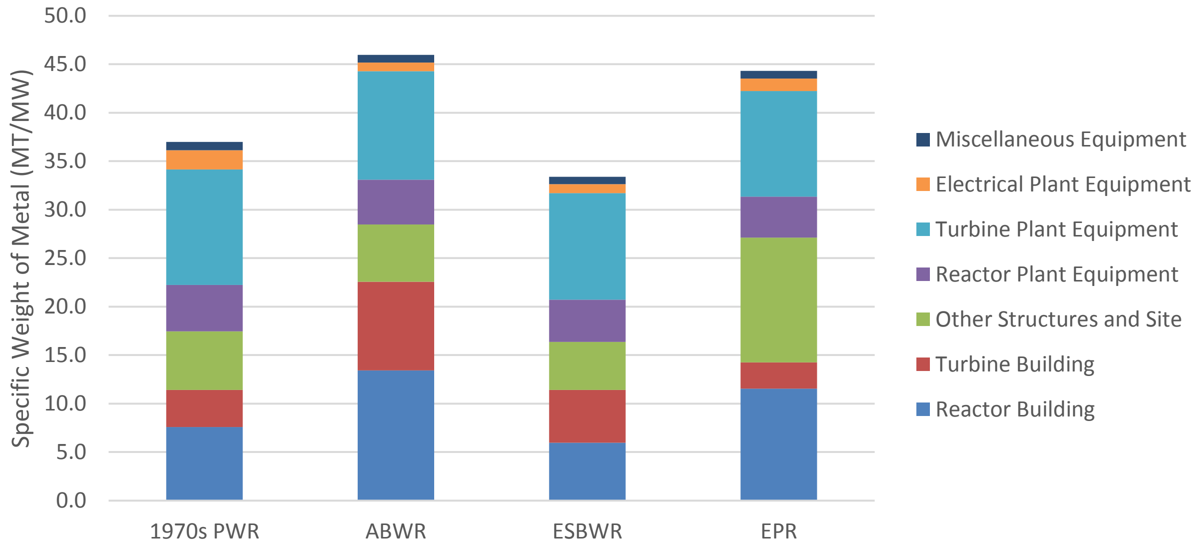


Figure 22. Metal usage in four different reactor designs (Peterson et al. 2005).

Using the steel commodity costs, labor rates, and composite labor wages from (EMWG 2007) as detailed in Table 10, Table 12, and Table 13 the breakdown labor and material cost of structural steel was found for a typical 1,000 MWe PWR using commodity amounts from (Bryan and Dudley 1974). This is depicted in Figure 23. The total cost of structural steel is estimated at $143.61/kWe.

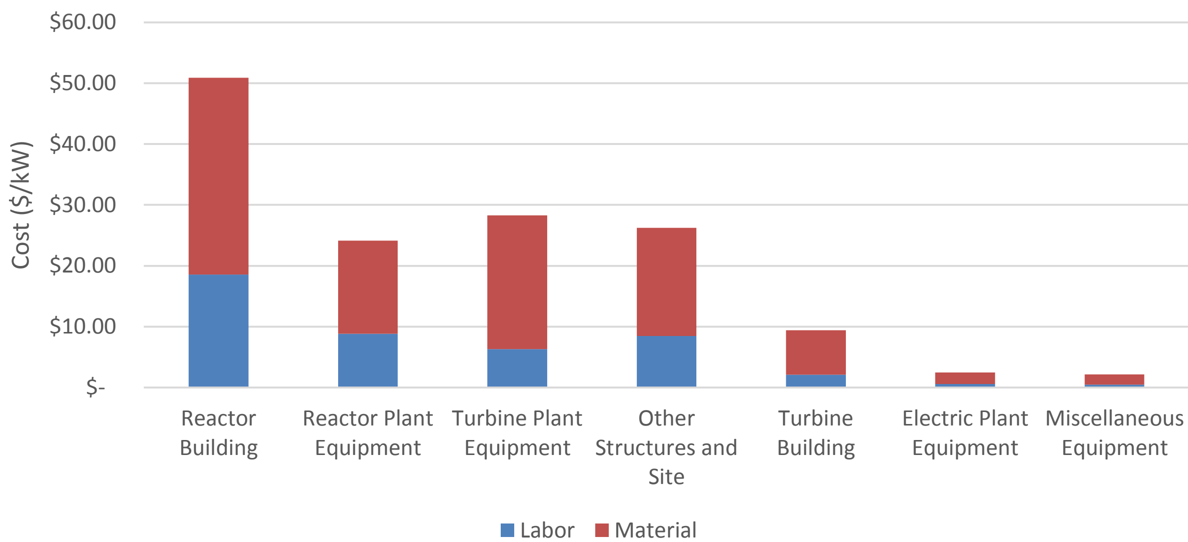


Figure 23. Steel labor and material cost breakdown by account of a typical 1,000 MWe PWR.

The structures and site account makes up a majority of the steel in the plant. This is because structures and site consists mainly of buildings, which require a large amount of steel (rebar). The equipment accounts also have substantial amounts of steel. The steel cost comprises about 32% labor costs and 68% material cost.

A parameterization is performed on the installation rate of structural steel. It is shown in Figure 24. The installation time is reduced down to 50% of the values in Table 13. At a 50% reduction, the estimated cost of steel decreases to 84% of its original value (from $143.61/kWe to $120.96/kWe).

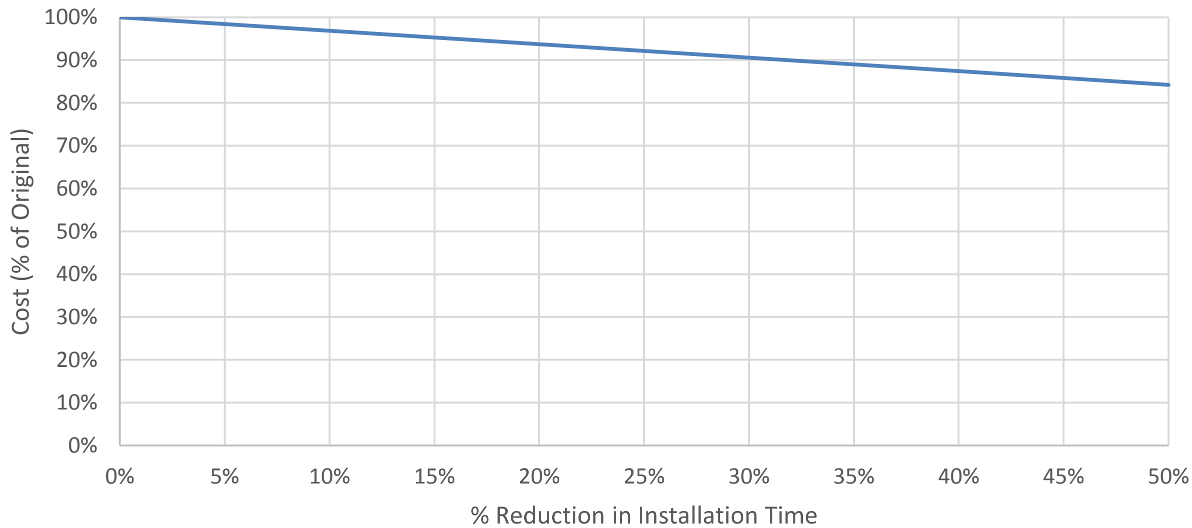


Figure 24. Steel installation time parameterization.

This shows that a reduction of 1% in installation time of steel results in a 0.3% reduction in total cost of steel. Installation times for steel can be reduced through many of the same methods to reduce installation time for concrete: decreasing worker idle time, increasing worker productivity, and decreasing the number of workers necessary for tasks. This is accomplished through better project management and design of the reactor with construction in mind. Another way to decrease installation times is to increase the speed of processes.

5.2 Price of Nuclear Quality

Structures and components in a nuclear power plant are subjected to rigorous quality control measures in order to ensure low failure rates. This is because the consequence of a nuclear failure that leads to a release of radiation is severe.

Table 10 and Table 13 show the commodity prices and installation times for both nuclear grade equipment as well as non-nuclear grade equipment. The commodity price of nuclear grade concrete is 50% more than the price of non-nuclear grade concrete. The commodity price of structural steel is 120% more than the price of non-nuclear grade steel. The installation time of nuclear grade concrete is 33% to 105% more than the installation time of non-nuclear grade concrete. The installation time of structural steel is 345% more than the installation time of non-nuclear structural steel.

In order to determine how much the nuclear quality adds to the cost of concrete and steel, one must determine the cost of the commodities if they were all non-nuclear. Figure 25 shows the normal cost of concrete and structural steel with the nuclear grade installation rates and commodity prices for safety related systems as compared to the cost of concrete and structural steel with all non-nuclear grade installation rates and commodity prices using cost numbers from (EMWG 2007).

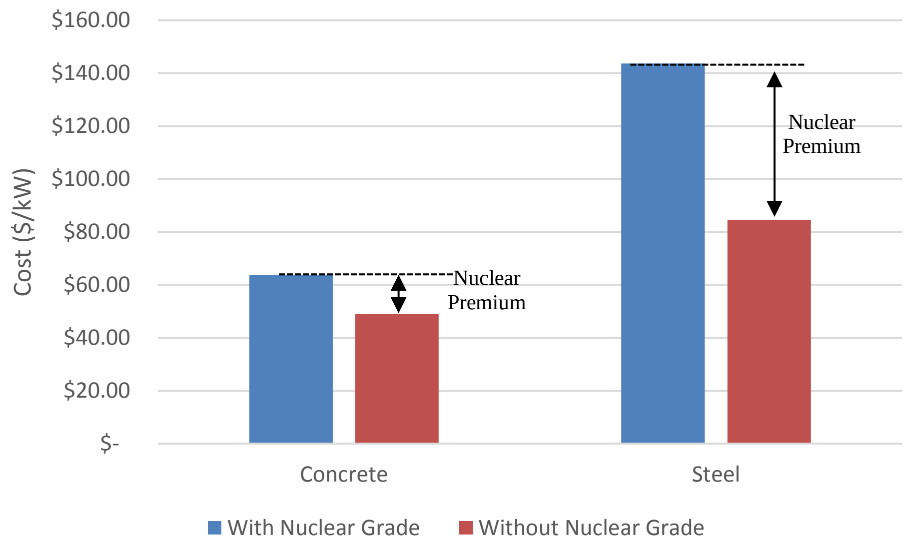


Figure 25. Commodity cost considering nuclear premium and excluding nuclear premium.

The nuclear premium of concrete is estimated at $14.88/kWe. This is 23% of the total concrete cost. The nuclear premium of structural steel is estimated at $59.06/kWe. This is 41% of the total structural steel cost.

5.3 Component Cost Scaling

Scaling exponents can be found in literature for many process systems and equipment. Scaling exponents for steam turbines, large heat exchangers (area over 100 m^2), and pumps are shown below in Table 14 from (EMWG 2007).

Table 14. Equipment scaling factors (EMWG 2007).

Equipment	Rating Unit	Scaling Exponent
Steam turbine	Power (MW)	0.50
Pump and motor	Horsepower	0.41
Heat exchanger over 100 m^2	Area (m^2)	0.62

5.3.1 Steam Turbine

The steam turbine is scaled based upon its power rating. The scaling exponent is 0.50. The scaling equation is shown below in Equation 2.

$$Cost_{turbine,b} = Cost_{turbine,a} \left(\frac{P_{turbine,b}}{P_{turbine,a}} \right)^{0.50} \quad [2]$$

The power rating of the steam turbine is equal to the electric power rating of the nuclear power plant, $P_{turbine} = P_e$. Therefore, the cost scaling factor for turbine cost based upon plant size is shown below in Equation 3.

$$Cost_{turbine,b} = Cost_{turbine,a} \left(\frac{P_{e,b}}{P_{e,a}} \right)^{0.50} \quad [3]$$

5.3.2 Reactor Coolant Pumps

The reactor coolant pumps are scaled based upon their horsepower. The scaling exponent is 0.41. The scaling equation is shown below in Equation 4.

$$Cost_{pump,b} = Cost_{pump,a}\left(\frac{hp_{pump,b}}{hp_{pump,a}}\right)^{0.41} \quad [4]$$

Horsepower for a pump is a function of mass flow rate, pressure rise, efficiency, and fluid density. The relationship is shown below in Equation 5.

$$hp_{pump} = \frac{\dot{m}\Delta P}{\eta_{pump}\rho} \quad [5]$$

The mass flow rate can be found as a function of reactor thermal power, specific heat of the coolant, and the temperature rise over the core. This is shown in Equation 6.

$$\dot{m} = \frac{\dot{Q}_{th}}{c\Delta T} = \frac{P_e}{\eta_{th}c\Delta T} \quad [6]$$

This relationship was checked against four LWR reactor designs with published mass flow rates, core thermal powers, and temperature rises. The relationship and the outcome for the four reactors are shown in Figure 26. As can be seen, there is alignment between the published mass flow rates and Equation 6.

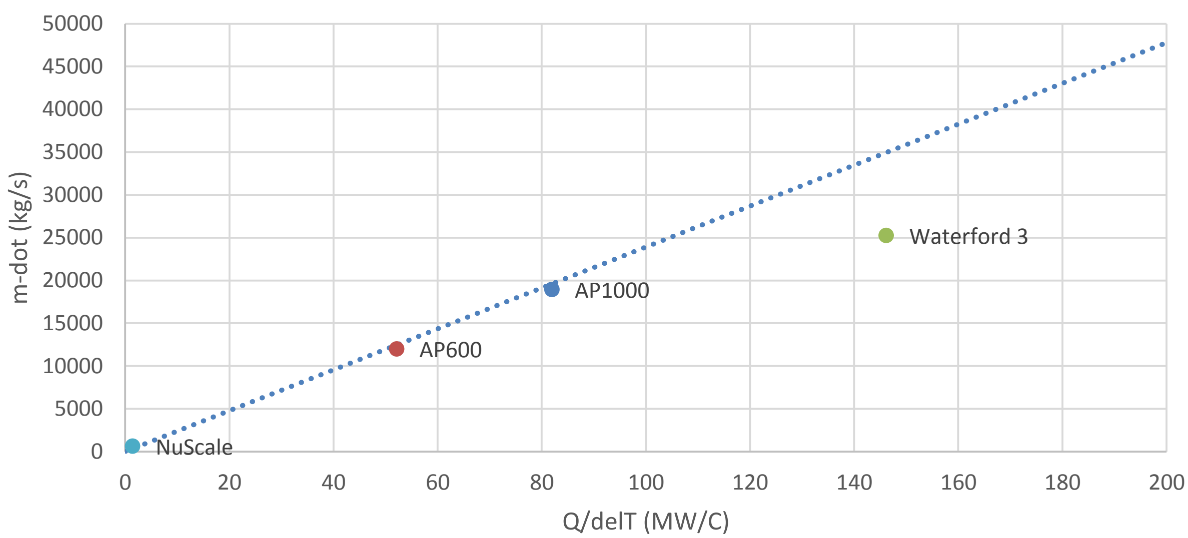


Figure 26. Mass flow rate equation benchmark as a function of power/temperature increase.

Combining Equations 5 and 6 produces Equation 7, which is the horsepower of a pump as a function of the electric power rating of a nuclear power plant.

$$hp_{pump} = \frac{P_e\Delta P}{\eta_{pump}\rho\eta_{th}c\Delta T} \quad [7]$$

Combining Equation 7 with Equation 4 arrives at Equation 8 which calculates the cost scaling of reactor coolant pumps based upon plant size. If all parameters are assumed constant, except for the plant size, Equation 9 is used.

$$Cost_{pump,b} = Cost_{pump,a} \left(\frac{\frac{P_{e,b} \Delta P_b}{\eta_{pump,b} \rho_b \eta_{th,b} c_b \Delta T_b}}{\frac{P_{e,a} \Delta P_a}{\eta_{pump,a} \rho_a \eta_{th,a} c_a \Delta T_a}} \right)^{0.41} \quad [8]$$

$$Cost_{pump,b} = Cost_{pump,a} \left(\frac{P_{e,b}}{P_{e,a}} \right)^{0.41} \quad [9]$$

5.3.3 Steam Generator

The steam generators are scaled based upon their total heat transfer area. The scaling exponent is 0.62. The scaling equation is shown below in Equation 10.

$$Cost_{steamgenerator,b} = Cost_{steamgenerator,a} \left(\frac{A_{steamgenerator,b}}{A_{steamgenerator,a}} \right)^{0.62} \quad [10]$$

Total heat transfer area for a steam generator is a function of overall heat transfer coefficient, core thermal power, and temperature difference between the primary and secondary side. The relationship is shown below in Equation 11.

$$A = \frac{\dot{Q}_{th}}{U \Delta T} = \frac{P_e}{\eta_{th} U \Delta T} \quad [11]$$

Combining Equations 10 and 11 will arrive at the cost scaling equation for a steam generator based upon plant size, Equation 12. If all parameters are assumed constant, except for the plant size, Equation 13 is used.

$$Cost_{steamgenerator,b} = Cost_{steamgenerator,a} \left(\frac{\frac{P_{e,b}}{\eta_{th,b} U_b \Delta T_b}}{\frac{P_{e,a}}{\eta_{th,a} U_a \Delta T_a}} \right)^{0.62} \quad [12]$$

$$Cost_{steamgenerator,b} = Cost_{steamgenerator,a} \left(\frac{P_{e,b}}{P_{e,a}} \right)^{0.62} \quad [13]$$

5.3.4 Cost Scaling Curves

The cost scaling equations for the steam turbine, reactor coolant pumps, and steam generators (Equations 3, 9, and 13) are plotted in Figure 27. The y-axis of the plot depicts the relative cost for the component as compared to the component cost for a 1,000 MWe reactor.

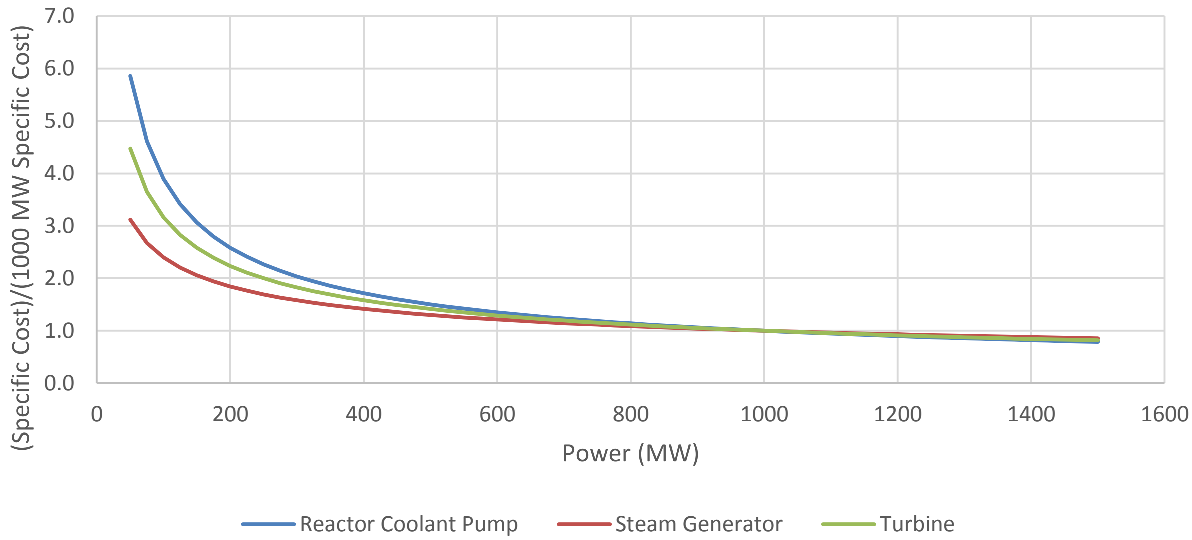


Figure 27. Cost scaling curves for the steam turbine, reactor coolant pumps, and steam generator.

The reactor coolant pump scales the best with reactor size. The steam generator scales the least with reactor size. This is clearly seen in the magnitude of the scaling exponents.

6. FIRST-OF-A-KIND COSTS

FOAK reactors will be more expensive than the consecutive reactor of the same technology. This is because there are unexpected additional costs associated with trying to commercialize a new technology. However, after the first reactor, there will be learning benefits in the construction crew that constructs the reactor as well as the construction management in charge of designing the construction schedule for the power plant construction.

The cost of reactor number k in a series can be estimated as described in Equation 14.

$$Cost_k = Cost_{FOAK} k^R \qquad [14]$$

where R is

$$\frac{-\log(1 - learning\ rate)}{\log(2)}$$

The NOAK reactor will be the lowest cost that one can achieve by learning. It is a value based upon the learning rate as well as number of reactors built until the NOAK.

Assuming there is a scaling factor 0.6 between the size (rated power) of nuclear power plants and the FOAK cost of a 1,000 MWe nuclear power plant is $6,000/kWe, then the cost of four different sized nuclear power plants as they transition from FOAK to NOAK is depicted in Figure 28. The FOAK costs for the four reactor sizes, 250 MW, 500 MW, 1,000 MW and 1,500 MW, are $10,447/kWe, $7,917/kWe, $6,000/kWe, and $5,102/kWe, respectively. The assumed learning rate is 4.5%.

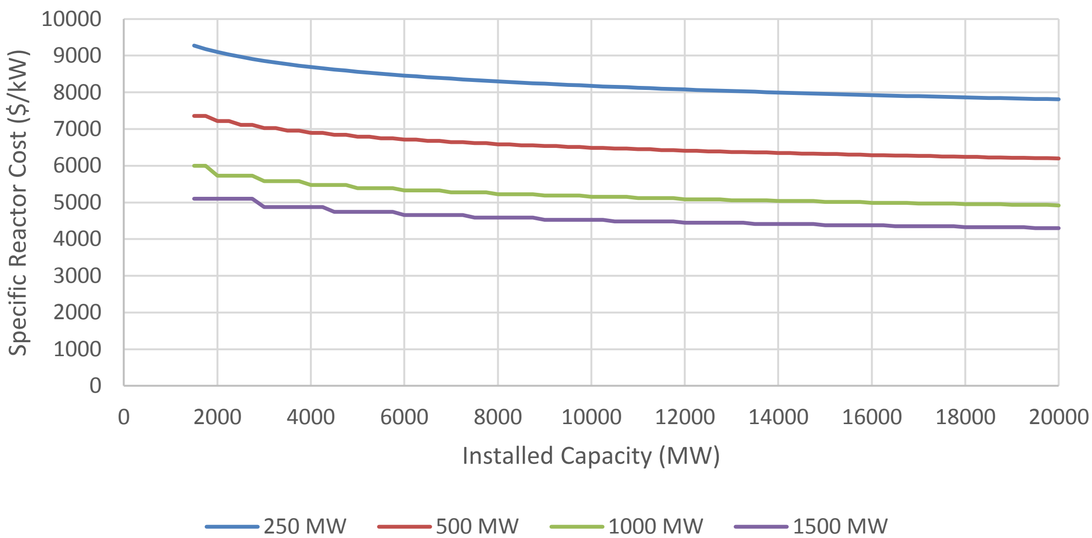


Figure 28. Transition from first-of-a-kind to nth-of-a-kind for selected reactor sizes.

As can be seen in Figure 28, for a smaller reactor, the cost will drop to an NOAK cost at a lower total installed capacity. This is because there are more units constructed for a given total installed capacity. In 20 GW of installed power, there are 80 250 MW reactors built but only 13 1,500 MW reactors built.

The FOAK premium is the amount of extra money paid over NOAK costs until NOAK costs are reached. It is described in Equation 15.

$$Premium = \sum_{k=1}^{total} (Cost_k - Cost_{NOAK}) \qquad [15]$$

Combining Equations 14 and 15 and simplifying results in Equation 16.

$$Premium = Cost_{FOAK}\left(\sum_{k=1}^{total} k^R\right) - k(Cost_{NOAK}) \quad [16]$$

Two parameterizations were performed: plant size and learning rate. These are described in the following sections.

6.1 First-of-a-Kind Premium Based on Plant Size

The FOAK premium is distributed amongst the first 20 GW of installation. The assumed learning rate for all reactor sizes for this analysis is 4.5%. In reality, the learning rate varies greatly with maturity of design, among other factors. The effect of learning rate on nuclear premium is explored in the next section. The assumed scaling exponent between FOAK costs based upon reactor size is 0.6. The FOAK cost for a 1,000 MW reactor is $6,000/kWe.

The NOAK cost is assumed to be when there is less than a 1% difference between consecutive reactor builds. The number of units to reach NOAK costs is shown in Equations 17 and 18.

$$0.99 = \frac{Cost_{k+1}}{Cost_k} = \frac{(k+1)^R}{k^R} \quad [17]$$

$$k = \frac{1}{\sqrt[R]{0.99} - 1} \quad [18]$$

For a learning rate of 4.5%, it takes seven reactors to reach NOAK. The parameterization results are shown in Figure 29.

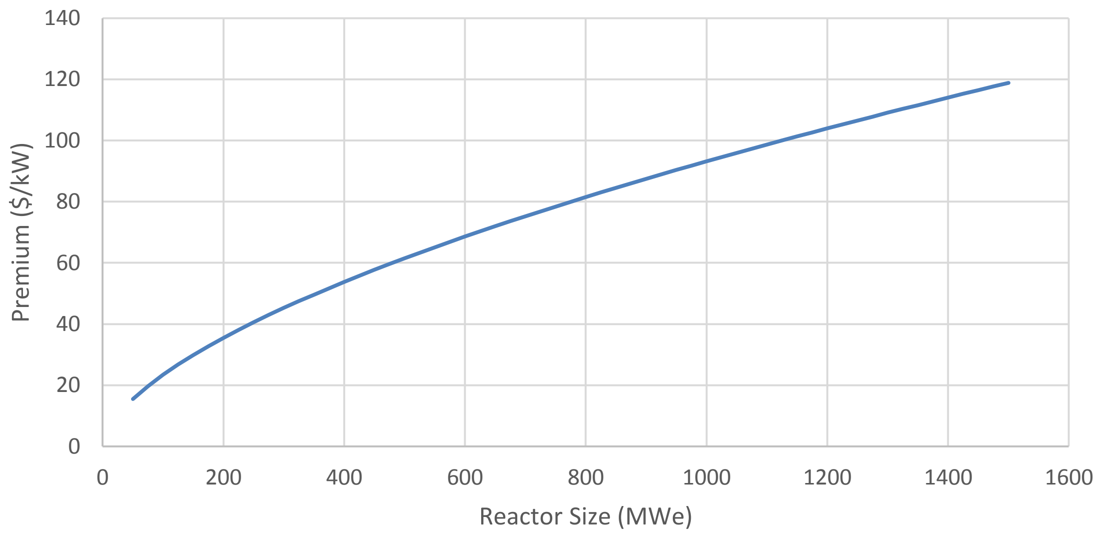


Figure 29. First-of-a-kind premium as a function of reactor size.

As can be seen, the premium decreases as reactor size decreases. This is because it takes a shorter amount of time to reach NOAK costs.

6.2 First-of-a-Kind Premium Based on Learning Rate

The FOAK premium is distributed amongst the first 20 GW of installation. The assumed reactor size is 1,000 MW with a FOAK cost of $6,000/kWe and a NOAK cost of $5,500/kWe. The parameterization results are shown in Figure 30.

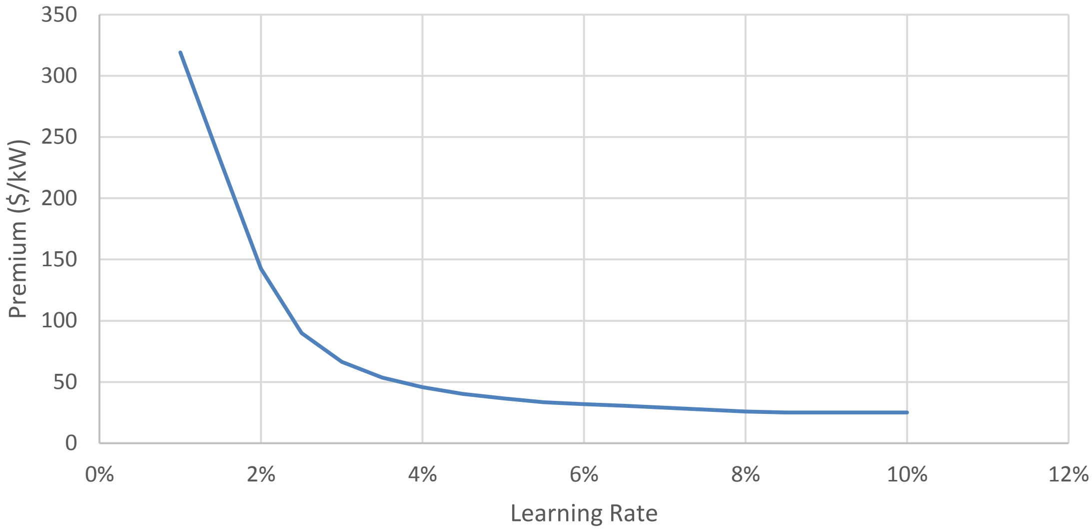


Figure 30. First-of-a-kind premium as a function of learning rate.

As expected, the premium decreases as learning rate increases. There is a sharp decline initially but the marginal benefit of increasing learning rate after about 6% is small. This shows the importance of trying to reach high learning rates. Higher learning rates will occur if the same construction crew (including the management) and an engineering procurement construction company is used in consecutive reactor builds. If the nuclear industry invests in higher learning rates by instituting programs that document and share lessons learned in nuclear construction, the FOAK premium for constructing nuclear reactors will decrease.

7. RESEARCH OPPORTUNITIES FOR LWR COST REDUCTION

This report demonstrates the importance of construction activities in the overall cost of LWR construction. This should be the area of focus for cost reduction. This section identifies three research areas that should be pursued to assist the nuclear industry reduce LWR costs: (1) construction expertise in research, (2) current designs for constructability, and (3) cost-benefit analysis of nuclear premium.

7.1 Include Construction Expertise in Research

A majority of the most beneficial cost reduction activities come from increasing the efficiency of construction. There are several proposed methods, from modularization to use of seismic isolators. However, the realistic implementation of these methods on a construction project as well as the realistic cost savings needs to be determined. **There should be a study on potential cost saving construction techniques in which the potential of each technique is rated based upon the feasibility and monetary savings**. In this study, there needs to be experts that have large project construction experience involved in determining these ratings.

7.2 Evaluate Current Designs for Constructability

Reactors need to be designed with construction in mind from the onset. It is not the complicated reactor technology that is expensive, it is the construction. Reactor technology should be designed to be constructed in the easiest and most efficient manner.

For designs that are already started or nearing completion, research should be done to determine how easy it is to construct the reactor, "constructability". This includes not only on-site construction, but also fabrication of any materials and equipment that will be built offsite and transported onsite. Constructability should be a criterion in determining the worth of a reactor design.

7.3 Perform a Cost-Benefit Analysis of Nuclear Premium

It was demonstrated that there is a significant nuclear premium associated with using nuclear grade commodities. There are other areas of construction that have this nuclear premium. The purpose of higher standards and quality control for safety-related systems is to reduce failure rates. There needs to be an in-depth analysis of the exact benefit from requiring the nuclear grade quality. There is no such study that quantitatively describes the decrease in failure rate as a result of using nuclear grade quality. Once this is quantitatively assessed, then a cost-benefit analysis should be performed to see if there is a way to achieve this reduction in failure rate in a more cost-effective manner.

8. CONCLUSIONS

This report outlined the main costs of LWR construction projects. It was found that it is not the nuclear technology itself that is a cost driver; rather it is the cost of a large-scale construction project that is regulated by strict nuclear standards that is the main cost driver. This conclusion has several important implications.

First, since the specific nuclear technology is not a cost driver, then constructing a different LWR technology, for example, advanced light water reactors, should not have a large effect on cost. Therefore, if the desire is to decrease the total cost, then more emphasis should be placed on construction than technology when designing a new reactor. This means that more time should be invested in constructability during the design phase. The experts can offer valuable insight into how easy it will be to construct and manufacture the design. Having a design that is easy to construct from the beginning means that there will not be any design changes during construction due to aspects of the design that cannot feasibly be constructed or fabricated. In addition, emphasizing high quality construction management during the construction phase will mitigate the cost impact of design changes and will reduce the cost impact of rework.

The second implication is that the nuclear standards associated with the construction of a reactor will cause a real cost burden to the owner. The reason for having strict standards is because it will lower the failure probability. This is important because the consequence of a nuclear incident is so severe. However, there is little information on this cost-benefit trade off. Since it is shown here to be a large cost driver, this research and discussion needs to occur. The cost burden to industry could be reduced if the marginal change in failure rate is negligible.

The final implication concerns future generations of reactors. There are very good reasons for generating new and innovative reactor designs, such as high temperature reactors providing high temperature heat for industrial processes or small modular reactors providing a lower total capital investment barrier. Investing in innovative nuclear construction techniques could yield greater cost reductions per dollar spent than investments in new nuclear technologies.

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Appendix A

U.S. Electricity Market

The U.S. Department of Energy has an excellent summary of the U.S. electricity market entitled "United States Electricity Industry Primer" (DOE 2015). A summary of this primer is provided here.

The market for electricity in the U.S. is complex and involves many stakeholders: from utilities to merchant power plants to customers to government agencies. The power grid in the U.S. is composed of three main grid interconnections: Western Interconnection, Eastern Interconnection, and ERCOT Interconnection. Within each interconnection, there are many regional entities: either regional transmission organizations (RTOs) or independent system operators (ISOs). The roles of an ISO and an RTO are similar. An ISO is responsible for operating the region's electricity grid, administering the region's wholesale market, and providing reliability planning. An RTO is responsible for all of the above in addition to greater responsibility of coordinating, controlling, and monitoring the operation of the electric power system within their territory. In areas where there are no RTOs or ISOs, the electric utility will assume the function of an ISO/RTO. The Federal Energy Regulatory Commission regulates the ISOs/RTOs as well as the utilities operating in regions without ISOs or RTOs. The FERC is responsible for ensuring that electricity consumers have access to reliable, efficient, and sustainable energy services at a reasonable cost.

Electric utilities generate, transmit, and/or distribute electricity to customers. There are five main types of electric utilities in the U.S.: investor-owned utilities, public power utilities, cooperatives, federal power programs, and independent power producers. In general, there are two ways that electricity is generated, delivered, and sold: the traditional, regulated, and vertically integrated model and a competitive, tradable commodity model. Figures A-1 and A-2 below show the differences between these two models of the electricity supply system (DOE 2002).

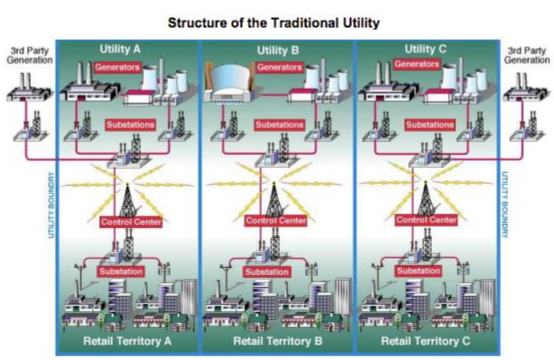

Figure A-1. Structure of the Traditional Utility (DOE 2002)

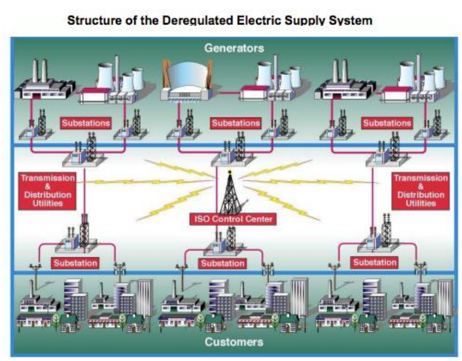

Figure A-2. Structure of the Competitive Electricity Market (DOE 2002)

In a regulated market, a vertically integrated utility generates, transmits, and distributes all of the electricity in a given region. They own all or part of the power plants and transmission lines in that region, or they purchase power through contracts. Because the vertically integrated utility controls most of the market in its region, the prices that consumers pay are based on rates that are monitored and adjusted by state regulatory commissions. In a competitive/unregulated market, electricity is bought and sold on the wholesale market. Electricity producers offer electricity at given prices to load serving entities. ISOs and RTOs administer the market and dispatch the electricity generators in accordance to market rules and demand. These are regulated by FERC. The retail electricity market is the market in which the provider sells electricity to the consumer. The price at which this electricity is sold (the retail price) is regulated in all states, regardless of competition or not. Some states have a capacity market. The purpose of these markets is to ensure that there are adequate operating reserves to provide electricity should demand exceed projections.

Appendix B

Electricity Market Economics Glossary

The economics of the electricity market is a field with is greatly studied and is often fast-evolving. Appendix A describes the electricity market in the United States. This Appendix provides a glossary of terms used to describe the economics of electricity markets.

Capacity Factor (CF)

This is the percentage of actual electricity generated by a power plant as compared to the maximum possible electricity output. Capacity factors can be calculated on any time basis, from a one-minute capacity factor to an annual capacity factor and beyond.

$$CF_{for\ a\ time\ T} = \frac{actual\ electricity\ output}{capacity\ \times\ T}$$

Base Load versus Peak Load

Base load is the demand that is constant throughout the whole day (such as the demand by refrigerators, ventilation systems, etc.). Peak load is the fluctuation of demand throughout the day (as caused by turning on lights during the day, watching TV at night, etc.). Demand is typically lowest in the very early morning and highest in the early evening. The cost of each generating source depends on its capacity factor, as seen in Figure B-1. An example of a base load power producer is natural gas. Base load plants provide the cheapest power at high capacity factors. An example of a base load power producer is nuclear.

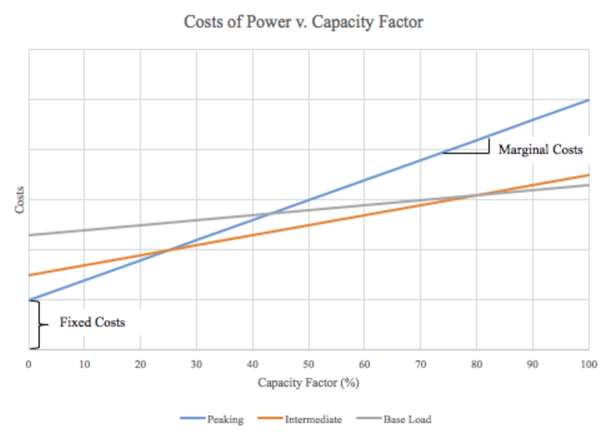

Figure B-1. Peaking plants provide the cheapest power at low capacity factors.

Intermittent versus Dispatchable

Intermittent power generators have different electricity generation capabilities at different times, often due to external conditions such as weather. Wind and solar are both intermittent. Dispatchable power generators can be turned on and off as needed. Natural gas is dispatchable.

Levelized Cost of Electricity (LCOE)

This is the cost of electricity that would make the present value of a new power generation project zero. In other words, it is the cost of electricity that would allow the power plant project to break even at the end of the project's life.

$$LCOE = \frac{sum\ of\ costs\ over\ lifetime\ of\ project}{total\ electricity\ produced\ over\ lifetime\ of\ project}$$

$$LCOE = \frac{\sum \left[\frac{investment\ costs_t + O\&M\ costs_t + fuel\ costs_t}{(1 + discount\ rate_t)^t}\right]}{Lifetime\ \times\ Capacity\ \times\ Capacity\ Factor}$$

For example, consider a 500MW power plant with a lifetime of 20 years. It will cost $3 billion spread evenly over 3 years to construct. Afterwards, it will incur annual costs of $20 million for O&M and fuel. It has a decommissioning cost of $1 billion over the year following the cease of operation. Its capacity factor is 80% and assumed discount rate is 10%.

$$LCOE = \frac{\frac{\$1B}{1.1^{-3}} + \frac{\$1B}{1.1^{-2}} + \frac{\$1B}{1.1^{-1}} + \frac{\$20M}{1.1^{0}} + \frac{\$20M}{1.1^{1}} + \cdots + \frac{\$20M}{1.1^{19}} + \frac{\$1B}{1.1^{20}}}{(20\ y)\left(\frac{8766h}{year}\right)(500MW)(0.8)} = \$56.71/MWh$$

<u>Levelized Avoided Cost of Electricity (LACE)</u>

This is the cost to the grid to meet the demand that is otherwise displaced by the new generation project. Variations in demand as well the current fleet of electricity generators are factors in determining this. The avoided cost is typically represented by the revenue that the power plant project earns. **Note that the project with the highest LACE – LCOE (revenue-cost) has the highest economic value.**

$$LACE = \frac{sum\ of\ avoided\ costs\ over\ lifetime\ of\ project}{total\ electricity\ produced\ over\ lifetime\ of\ project}$$

$$LCOE = \frac{\sum \left[\frac{price\ of\ electricity_t \times generation_t}{(1 + discount\ rate_t)^t}\right]}{Lifetime\ \times\ Capacity\ \times\ Capacity\ Factor}$$

Let us consider the same power plant as in the LCOE section. For simplicity, we consider only two seasons: summer/fall and winter/spring. In this summer/fall, the electricity prices are $60/MWh and the capacity factor of the plant is 90%. In the winter/spring, the electricity prices are $90/MWh and the capacity factor of the plant is 70%.

$$LACE = \frac{\sum_{t=0}^{19} \frac{\left(\frac{4383h}{season}\right)(500MW)(0.9)\left(\frac{\$60}{MWh}\right) + \left(\frac{4383h}{season}\right)(500MW)(0.7)\left(\frac{\$90}{MWh}\right)}{1.1^t}}{(20\ y)\left(\frac{8766h}{year}\right)(500MW)(0.8)} = \$36.00/MWh$$

The economic value of this plant is $36.00/MWh - $56.71/MWh = -$20.71. It has a negative value. Without additional revenue or decreased costs, the plant will not be economical.