Scenario Modeling for Feasibility Assessment of Nuclear Power Plant Construction Projects

By

Kathryn E. Biegel

Submitted to the Department of Nuclear Science and Engineering
In Partial Fulfillment of the Requirements for the Degree of
Bachelor of Science in Nuclear Science and Engineering
at the
Massachusetts Institute of Technology
June 2015

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Abstract

In historical and current experience, the economics of nuclear power have proven to be problematic for utility companies. Construction costs and schedules have proven to be highly unpredictable, with the average reactor construction project costing two to three times more than its initial budget and taking almost twice as long to complete as expected. The causes of this phenomenon have not been well-characterized, even two decades after the last new reactor was brought online in 1996. Scenario generation can provide useful information about the economic viability of nuclear construction projects over a variety of parameter spaces without having to make prescriptive assertions about likely single values for delay and other difficult-to-predict parameters. The MEERKAT model creates scenarios over two different reactor types (Westinghouse AP1000 and NuScale SMR plant); three delay cases (optimistic, median, and pessimistic based on historical data); and six different utility company credit ratings (which translate into varying costs of capital). MEERKAT outputs the levelized cost of electricity (LCOE) for each scenario and compares them to average electricity prices for a number of regions in the United States. These scenarios produce levelized costs of electricity (LCOEs) that are not competitive in a deregulated market in any case, and which may be competitive in regulated markets under certain optimistic conditions. If the AP1000 is considered as more credit-stressful than the SMR project, the SMR becomes more competitive with the AP1000, but the projects' viability in the wider market remains unchanged. However, in general terms the smaller up-front cost of the SMR makes it a more feasible endeavor for a wider variety of utility companies, increasing the potential customer base for nuclear power generation units.

Thesis supervisor: R. Scott Kemp
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Acknowledgements

To Prof. Kemp, for mentoring me through designing and executing my own research project, for helping me discover a passion for construction, and for being a fount of patience and good advice. He made me scrutinize everything I held dear and I've grown a lot as a researcher and a person because of it. It's been a privilege to have him as an advisor.

To my mom, my role model, who works hard every day of her life and has fought so hard for me to be able to attend MIT. I wouldn't be here without you.

To Mike, whose generous assistance and superhuman kindness made my education possible.

To my friends, who got me through tough times and happy times, helped me make serious life choices, and kept me sane. I'm so lucky to have had such a supportive, fun, and inspiring group of people by my side.

And to Jake, for all your encouragement and for being my sounding board over the past year and a half. You're a terrible backseat driver but I couldn't have asked for anyone more supportive in non-vehicle-related contexts.

To the making of these fateful decisions, the United States pledges before you–and therefore before the world–its determination to help solve the fearful atomic dilemma: to devote its entire heart and mind to find the way by which the miraculous inventiveness of man shall not be devoted to his death, but consecrated to his life.

— President Dwight D. Eisenhower, 8 Dec 1953

Contents

1 Introduction

> *An academic reactor or reactor plant almost always has the following basic characteristics: (1) It is simple. (2) It is small. (3) It is cheap. (4) It is light. (5) It can be built very quickly. (6) It is very flexible in purpose. (7) Very little development will be required. It will use off-the-shelf components. (8) The reactor is in the study phase. It is not being built now.*
>
> *On the other hand, a practical reactor can be distinguished by the following characteristics: (1) It is being built now. (2) It is behind schedule. (3) It requires an immense amount of development on apparently trivial items. (4) It is very expensive. (5) It takes a long time to build because of its engineering development problems. (6) It is large. (7) It is heavy. (8) It is complicated.*
>
> — Admiral Hyman G. Rickover, 5 Jun 1970

This relentlessly practical mindset has characterized the choices made about nuclear power technology since the very beginning. The design for the reactor for the USS *Nautilus*, the first nuclear submarine, was driven by the need to beat the Soviets to a nuclear ship [2]. Funding for reactor concepts under the AEC was partially based on how quickly the technology could be mastered and commercialized, again in no small measure thanks to competition with the USSR for this great scientific achievement[1] [2]. Eventually, the industry backing of the Light Water Reactor (LWR) set it so far ahead of its competition that it became the only real commercial option; all other designs were relegated to academia or sought markets overseas. LWRs rapidly scaled up in capacity in order to capture economies of scale in construction and operation. By 1985, it seemed infeasible that nuclear power could take any other form, given the massive R&D and construction experience lead enjoyed by the light-water designs [1] [2].

However, by that time, it had also become apparent to most observers that something was fundamentally broken about nuclear power. For two decades, reactor construction projects had been coming in hugely over budget and over schedule. The record was set by Diablo Canyon Unit 1, which cost 7.4 times more than its original budget, but the average project came in two to three times more expensive than had been planned [3]. Even today, the causes for these cost increases are poorly understood. Even better-than-predicted improvements in operational performance (an astounding jump from 65% and "deteriorating" capacity factor in 1982 [4] [5] to an industry-wide stable average of 91.7% capacity factor in 2014 [6]) couldn't offset the blow to utilities' finances from the up-front costs. Many nuclear utilities saw their credit ratings erode as a result of these projects, leading to long-term impairment of their ability to borrow funds [7]. These problems were compounded by such issues as waste and public opposition following the Three Mile Island and Chernobyl accidents [8]. The last new reactor in the United States, Watts Bar Unit 1 in Tennessee, came online in 1996, by which time the power industry was more than ready to altogether abandon the idea of further nuclear expansion.

Amid rising concerns about carbon emissions and global climate change, however, nuclear power is experiencing a new relevance in the dialogue about power generation. In 2013, 32% of greenhouse gas emissions in the US came from electricity production [9]. Nuclear energy is low-carbon, can provide baseload power, has a small physical footprint, and doesn't require major alterations to the infrastructure and operation of the power grid. However, the old economic problems must be resolved or mitigated before nuclear power can fulfill these promises.

It is sometimes asserted that negative public opinion is the major cause for the failure of nuclear power. However, public opposition was only cited as a cause in four reactor project cancellations in the past (out of 100; the leading causes were overwhelmingly economic) [8]. Additionally, even in today's relatively favorable public-opinion climate, the new reactors being constructed at Vogtle and V.C. Summer are experiencing financial difficulties in line with historical experience [10] [11].

In light of this recent imperative, a new paradigm for reactor design has been seriously developed for the first time: that of the small, modular reactor (SMR). The core reactor technology for the various SMR concepts varies wildly; some are evolutionary improvements on traditional LWRs, while others are true "Generation IV" designs utilizing advanced fuels, coolants, and core geometries. Their uniting feature, however, is their small size and constructability. SMR designers assert that smaller can also be better, offering advantages in flexibility and affordability. No SMR concept has yet received a Final Design Approval or been constructed in the United States, thereby failing Rickover's test for practicality. However, this approach merits serious consideration: given the nuclear industry's track record with construction costs, it is unclear that forging ahead with traditional technologies continues to be a wise strategy.

At the same time, waiting for the best possible technology to emerge from the pack is also unlikely to achieve the desired outcomes of an expansion in nuclear power and a drastic reduction in carbon emissions. This optimal design, regardless of how elegant, must have all its design work completed, be licensed by the NRC, attract industry customers, and be constructed before it can begin to have an impact. The timeline for this development process is fundamentally limited: given the immense effort into the recent and ongoing twenty-year life extensions for these plants, it might be unwise to count on these reactors being allowed to operate past 60 years [12]. This leaves approximately 20 years until the vast majority of nuclear reactors in the US go offline permanently. If this void is not to be filled by fossil fuels, a new nuclear reactor design must be ready to step into that gap. Many of the truly innovative Generation IV designs are unlikely to be ready for deployment on this timescale.

For the purposes of this study, a "compromise" SMR technology has been chosen for detailed examination: the NuScale SMR, an Integral Pressurized Water Reactor. Of all the SMR concepts in development, the NuScale SMR is a strong candidate for near-term design completion, owing to the already-advanced state of the design and the funding NuScale has secured from industry and government backers [13]. Their proposal also offers major safety innovations over a traditional LWR [14]. These characteristics make it an ideal choice for a representative SMR.

1.1 Project Goals

The goal of this study is investigate the economic viability of SMR and large LWR construction projects. A number of scenarios will be generated by the MEERKAT model, created for this study, in order to explore the impact of three major parameters:

- reactor type (AP1000 or NuScale SMR);

- degree of delay experienced during the project;
- and the credit rating of the parent utility.

Each project will be evaluated based on levelized cost of electricity (LCOE). The LCOE is the price a utility must charge for power from a new power plant in order to cover its construction loan payments, operating and maintenance costs, and fuel costs. The LCOEs produced from each scenario will be compared to actual electricity prices sampled from around the United States to provide context on how justifiable each project would be in various markets.

Additionally, data about the overall construction costs will be recorded and examined. Negative credit-rating impacts of risky projects generally stem from their large financial magnitude rather than byproduct figures like the LCOE [7], so discussions of cost-of-capital changes are better served by a discussion of total debt to be accrued.

2 Literature Review

The extant literature on nuclear power construction costs in the US can be divided into two relevant groups: work published prior to 1986, and work published later than 2000.

2.1 Historical Studies

The former group, published during the major nuclear construction era in the US, has largely lost its value over time for several reasons.

1. Much has changed in the past 30 years in the construction industry, the regulation of nuclear power, and reactor design, rendering many assumptions and methods of these studies unsuitable for present purposes.
2. The pre-1986 studies were conducted while a great deal of nuclear construction was still occurring; therefore, many cost and risk trends that are now relatively clear would not have been observable at the time.
3. The results of these studies have generally failed to withstand the test of time. Most concluded a much more positive outlook for nuclear power costs than actually came to pass, with many even predicting that nuclear power would soon become cost-competitive with coal-generated power. [15] [16] [17] [18] [19] [20]

The pre-1986 literature has been very useful in framing the history of this issue and providing some of the most complete datasets currently available. However, due to these three major issues, the applicability of these studies is fundamentally limited.

More recent research, while still susceptible to the third factor listed above, has the benefit of hindsight on the major construction period between 1965 and 1996. There have been several major studies published post-2000. The relevant conclusions of the two studies found most useful to this research are summarized below.

2.2 MIT: "The Future of Nuclear Power"

This 2003 study [21] examines a number of issues related to nuclear power, including economics, the fuel cycle, safety, waste disposal, and public opinion. The authors list cost reduction as one of the four primary obstacles to a widespread expansion of nuclear power. An update [22] to the cost section was issued in 2009 and contains more current assumptions about the economics of nuclear, as well as coal and natural gas. This report analyzed nuclear, coal, and natural gas generation technologies on a levelized cost of electricity basis.

The Update estimates the levelized cost of nuclear electricity to be 8.4 cents/kWh in 2007 dollars, equivalent to 9.9 cents/kWh in 2015 dollars. In the case where the utility could secure the same cost of capital for its nuclear project as it could for a coal or gas project, this cost decreases to 6.6 cents/kWh in 2007 terms, equivalent to 7.7 cents/kWh in 2015 terms.

2.3 UChicago: "The Economic Future of Nuclear Power"

This 2004 study [23] used contemporary estimates on the cost of nuclear power as a baseline to discuss the current and future prospects of nuclear energy relative to competing technologies, as well as possible support measures to increase its competitiveness.

The UChicago study used the best available estimates at the time for overnight costs of nuclear plants, evaluating a "mature" reactor design (traditional LWR), the AP1000, and the EPR, considering lead times of 5 and 7 years. In 2015 dollars, UChicago estimates an AP1000 LCOE of 7.0 cents/kWh for the 5-year case, and 8.1 cents/kWh for the 7-year case. These estimates are for a first-of-a-kind reactor.

3 Construction Project Finance

3.1 Levelized Cost of Electricity

The principal evaluation metric in this study is the Levelized Cost of Electricity (LCOE). The LCOE for a power plant project is the price a firm would have to charge for electricity produced from a certain plant to cover its loan repayments, operating and maintenance costs, and fuel costs. LCOE is a useful metric because it helps to put disparate projects on a relatively equal footing; larger plants cost more up front but also produce a larger revenue stream later on, and vice versa for small plants. If a prospective project's LCOE is too large compared to typical wholesale electricity prices for the firm's market, then the project is not justifiable.

LCOE will be calculated for the first year of operation, with the assumption that for subsequent years revenues and costs will scale with inflation. The only major change in LCOE occurs at the end of the loan repayment term, when the payments cease and operating costs and revenues become the only relevant factors.

3.2 Overnight Cost

One common metric for nuclear project costs is the *overnight cost.* Overnight cost is how much a project would cost if it were built instantaneously; e.g. it neglects the effects of interest on borrowed capital. Overnight cost is useful for projects whose time to completion is uncertain, since interest can be added back in if a certain construction time is assumed. In this study, the best overnight costs available have been modulated by a variety of lead times and interest rates to produce a spectrum of results on the true cost of a nuclear power project.

3.3 Cost of Capital

3.3.1 The Importance of Interest Rates

Due to the long lead times required for the construction of a nuclear power plant, the interest accrued on the construction loan during the construction period has an enormous effect on the final cost and viability of the project. Securing a favorable interest rate is a high priority for any utility seeking to build a nuclear plant. The terms *cost of capital* and *interest rate* will be used interchangeably.

3.3.2 Credit Ratings

A useful tool for lenders to determine an appropriate cost of capital is a firm's *credit rating.* A credit rating is an assessment of a company's creditworthiness based on a number of factors, including debt-to-asset ratios, regulatory environment, portfolio diversity, and decisions that increase or decrease uncertainty about the company's future. These ratings are intended to reflect the likelihood of a company defaulting on a loan, and how much capital an investor can expect to recover in that eventuality. A firm with a high credit rating is seen as unlikely to default, and the reverse is true for a firm with a low credit rating; credit rating thus tends to inversely correlate with interest rates on loans. A downgrade in credit rating can significantly affect a company's ability to secure reasonably-priced capital for long periods of time. [24] [25]

Credit ratings are issued by one of four evaluator firms: Moody's Investors Service, Standard & Poor's, Fitch, and DBRS. Each firm has its own methodology and ratings system, but their assessments tend to line up well with one another. These firms do not release their explicit formulae for calculating credit ratings. However, they do release more general "ratings grids" or evaluatory guidelines which provide qualitative information about the categories and factors considered in their decisions. Additionally, when a company's credit rating is changed, the rating institution usually publishes a "ratings action" document detailing the specifics of the rating change and the rationale behind it. These documents can provide interesting and useful insights into factors precipitating changes in the creditworthiness of various companies.

One particularly relevant trend apparent from ratings actions is the systematic ratings downgrades experienced by utilities that have engaged in nuclear construction projects. The Moody's report entitled "New Nuclear Generation: Ratings Pressure Increasing" [7] details the historical financial difficulties encountered by utilities in the midst and aftermath of new nuclear builds. Of the 48 utility companies that were evaluated during the 1965-1995 nuclear construction period, "two received rating upgrades, six went unchanged, and 40 had downgrades. Moreover, the average downgraded issuer fell four notches." (An *issuer* is a company being reviewed, and a *notch* is the smallest rating increment.) This document also details Moody's opinion that nuclear investments are inherently risky to most utility companies because they are very expensive relative to the total assets of these companies, characterizing these projects as "bet the farm endeavors" for most companies. Moody's considers nuclear power projects to be credit-negative, and is considering levying a special credit penalty on nuclear construction projects due to the abundance of negative past and current experiences. However, this effect is mostly related to the total magnitude of debt incurred. This may have positive credit and cost-of-capital implications for smaller nuclear projects like SMRs, which require a company to shoulder less total debt and take fewer financial precautions beforehand.

Utility companies tend to have credit ratings in the medium to upper-medium investment quality range due to the universal nature of their product and the relative predictability of their markets [7].

A term of note is the *credit spread.* The cost of capital usually has some long-term risk-free rate as its baseline and an additional levied cost based on the creditworthiness of the firm. The risk-free rate is often the U.S. Treasury long-term bond rate, and the extra cost is the spread. In this model, the spread is based on the firm's credit rating, hence the term credit spread.

3.3.3 Debt vs Equity

It is not typically in the economic interest of a company to maintain large amounts of cash on hand. Extra income beyond what is needed to cover short-term expenses is often redistributed to shareholders, or used to pay off debts early [26]. Therefore, when a utility begins a capital-intensive project, it will secure some of the required money from lenders (in the form of **debt**) and the rest from its own shareholders (in the form of **equity**).

The debt and equity available to a company usually come with different rates of return attached, although both rates usually take into account the company's credit rating. Debt tends to be available to utilities at a low cost (3-6% interest annually) [27]. The cost of equity to a utility tends to be in the 8-15% annual range [27].

It is often convenient to express these two interest rates as a single value, the Weighted Average Cost of Capital (WACC) taken as the weighted average of the two according to the debt/equity fraction:

$$\text{WACC} = \frac{\text{interest rate on debt} \cdot \text{amount of debt} + \text{interest rate on equity} \cdot \text{amount of equity}}{\text{amount of debt} + \text{amount of equity}} \tag{1}$$

For the purposes of this study, all projects are assumed to be funded by 50% debt and 50% equity.

3.4 Project Delay

The final cost of a nuclear power plant construction project is highly sensitive to the length of the construction period. Due to the compounding of interest, and discounts imposed on revenue streams beginning years in the future, longer-than-expected lead times can severely impair the project's economic viability. Nuclear construction projects seem to be especially susceptible to delays; of the 110 reactors completed in the United States, only one was finished prior to its scheduled completion date; the rest varied in delay from a few extra months to six extra years [3]. The universality of delay in these projects mandates its inclusion in this study.

3.5 Learning Effects

"Learning effects" are a type of capital cost reduction that occurs as repeated instances of a project are completed over time. As a company or industry gains experience with a certain project, the projects are liable to be completed with greater efficiency, fewer midstream design changes, and under more efficient regulatory procedures, decreasing the final cost. This effect has been observed with naval ships [28]. "First-of-a-kind" projects are often differentiated from "nth-of-a-kind" projects in cost-engineering literature, in that the latter is less expensive and more efficient due to learning effects.

Numerous sources make assertions about learning effects in nuclear power plant construction projects [28] [29] [14] [30] [31]. However, they were never definitively observed in the historical record of nuclear project costs in the US. While it is credible that learning may be observed in the future, it is beyond the scope of this study to evaluate the likelihood of learning effects manifesting as predicted by reactor designers and nuclear proponents. This study uses "first-of-a-kind" cost estimates, rather than learning-enhanced "nth-of-a-kind" cost estimates to avoid this additional uncertainty.

4 Electricity Markets in the United States

4.1 What is "The Grid"?

There are four main types of activities that make up the national power grid: generation, transmission, distribution, and retail [32].

- **Generation** is the creation of electricity from various fuel sources at power stations.
- **Transmission** takes electricity from the generators at extremely high voltage and passes it along to high-voltage customers and to distribution networks. Transmission lines are typically high-capacity and long-distance.
- **Distribution** accepts electricity from the transmission network and distributes it to medium- and low-voltage consumers. Distribution lines have smaller capacities and typically don't travel as far as transmission lines do.
- **Retail** is the actual act of selling power to consumers at the distribution level. Retailers don't build or own lines, but conduct all billing, metering, and customer-service activities.

When two or more of these services are provided by the same company, those services are **bundled**. Distribution and retail are very often bundled in all market types. As discussed below, various degrees of unbundling may be present in a given market depending on the regulatory setup.

4.2 Electricity Market Organization in the US

Electricity markets in the US are generally organized at the state or regional level, rather than at the federal level. The autonomy given to the states has resulted in highly non-uniform market structures across the country. However, markets in individual states or regions can be generally categorized as traditional or restructured markets.

4.3 Traditional Markets

In traditional markets, a single utility is awarded monopoly status for generation, transmission, and distribution of electricity in a given territorial franchise. In exchange, a Public Service Commission (PSC) is established for that region to regulate the operations of that utility. The utility makes a *rate case* to the PSC periodically, detailing its operational and capital costs and requesting a certain level of remuneration; the PSC can approve, deny, or negotiate the proposal. These utilities are usually limited by either a revenue cap or an electricity price cap. This system was introduced when electrification started to become widespread in the US in the early 1900s. [32] [33]

The traditional market structure offers a great deal of stability and risk reduction due to the centrality of investment planning. Agents under this scheme can often tolerate more risk due to some guarantee of return on investment on the part of the PSC [32]. Regulated utilities are often referred to as *vertically-integrated utilities* because they fulfill all the functions involved in the provision of electricity.

4.4 Restructured Markets

Restructured or "deregulated" markets are a relatively new idea worldwide; the first such market appeared in Chile in 1981, with a number of nations following suit. In the US, restructured markets exist in 16 states, with the rest retaining their traditional structure. The composition of these systems is not predictable: generation, distribution, and retail have typically been candidates for unbundling, but the actual result varies between states, regions, and even cities. [32] [33]

Restructured markets are less predictable than traditional markets, because no single market player has perfect information about the investment and operation decisions its competitors will make. This tends to result in utilities that tolerate lower risks on investments and lower interest rates, and in many cases has resulted in a proliferation of small utilities (often owning only a single power plant). However, restructured markets have been praised as more economically efficient, with competition driving down prices and incentivizing efficiency in capacity investment and in operation. [32] [33]

Restructured markets typically maintain at least two remnants of the traditional structure: transmission is nearly always traditionally regulated and remunerated; and retail and distribution are usually bundled together due to the extremely minor efficiency gains achievable through their separation. [32]

4.5 Market Outlook

Demand for electricity has grown almost monotonically since the first electrification efforts over a century ago. The U.S. Energy Information Administration (EIA) has recorded data since 1949 on electricity demand in the United States; data on demand growth over time are shown in Figure 1.

Growth has slowed dramatically over the years, even dipping into the negative range twice. Regional markets may be individually experiencing more or less demand growth than this national average indicates, but on the whole utility companies cannot expect to see a need for significant new capacity additions in the short term.

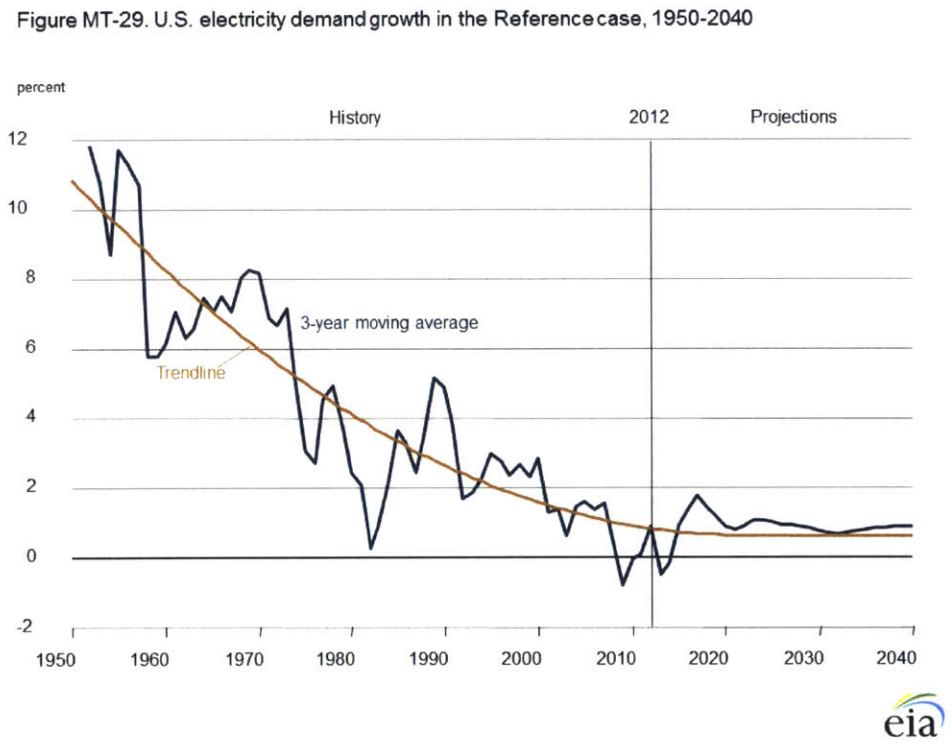

Figure MT-29. U.S. electricity demand growth in the Reference case, 1950-2040

Figure 1: U.S. electricity demand growth, 1952-2014, with projection to 2040. Line at 2012 does not indicate beginning of projected data. Source: EIA [54]

5 The Life Cycle of a Nuclear Power Plant Construction Project

A nuclear power plant experiences four main life-cycle phases, each with distinct cash flow sources and sinks: *preconstruction*, *construction*, *operation*, and *decommissioning.* For the purposes of this investigation, each phase will be considered separately. This information has been summarized from the comprehensive 1978 report "Planning, Design and Construction of Nuclear Power Plants: An Overview" [34].

5.1 Preconstruction

A power plant project begins long before any ground is broken. Preconstruction activities include NRC license applications, approvals by state and local authorities, land acquisition, vendor bid solicitations, and contracting decisions. These activities usually constitute a small percentage of the total project expenditures, but skillful preproject planning during this period can have a large impact on the success of the project later on.

5.2 Construction

The construction period includes all activities conducted between ground-breaking and first commercial operation of the power plant. Costs incurred in this period result, obviously, from on-site construction activities, but also include the costs of off-site construction-related activities such as the manufacturing of modules and components. The cost of capital plays an important role in the cash flow for this period; nuclear power plants, like most large infrastructure projects, are fully debt-financed.

5.3 Operation

The operations period is the longest of the four. During this time, the utility finally begins receiving income from electricity sales from the plant. At the same time, the utility is paying operations-and-maintenance and fuel costs, as well as paying off the construction loan and interest.

5.4 Decommissioning

At the end of a nuclear power plant's life, it must be decommissioned. The waste must be prepared for long-term storage, the radioactive plant components dealt with, and the site made safe for abandonment or reuse. The Nuclear Regulatory Commission has strict rules for the decommissioning process to ensure that workers and the public are kept safe in the short and long term.

6 The Reactors

6.1 The AP1000

6.1.1 AP1000 Reactor Overview

The AP1000 is an 1117-MW (electric) Pressurized Water Reactor (PWR), designed by Westinghouse [35] and certified by the NRC in 2006 [36]. The main innovation it offers over previous incarnations of the PWR are in its passive safety systems, which can ensure safe reactor shutdown and long-term cooldown in the absence of external power by exploiting natural circulation due to temperature differentials in fluid systems. Additionally, it is more volumetrically compact than older PWR designs, and requires less rebar and concrete. [37] [35]

There are four AP1000 reactor units currently under construction in the US: two are at the V. C. Summer site in South Carolina [38], and two are at the Vogtle site in Georgia [39]. Both projects are expansions of existing two-unit nuclear generating stations. The new Summer units are expected to come on-line in 2018, with the Vogtle units following in 2019-2020, but these dates are hard to predict with certainty and both projects have already experienced significant delays.

6.1.2 AP1000 Economic Characteristics

The AP1000 can offer a low levelized cost of electricity (LCOE) [37]. The AP1000's large capacity takes advantage of economies of scale; it is more fuel-efficient per unit power produced than a smaller reactor, and its construction loans are also lower per kilowatt. However, because it is large its total construction costs are much higher than those of an SMR. [29]

6.2 The NuScale SMR

6.2.1 NuScale SMR Reactor Overview

The NuScale SMR is an Integral Pressurized Water Reactor (IPWR). Each reactor module produces 45 MWe, and the plant itself can be built out with between 6 and 12 modules. Modules are fabricated off-site; at the job site modules are installed into individual slots in a below-grade pool. Each module operates completely independently of the others, so that units can be taken offline for maintenance and refueling without requiring a shutdown of the entire power station. Modules remain underwater all the time, and can be moved by overhead crane. The integral pressure vessel contains the entire primary loop, including the core, hot and cold legs, steam generator, and pressurizer. [14]

This scalable plant design offers extensive capacity flexibility to suit the needs of a wide variety of utility companies. The IPWR design, like the AP1000, makes extensive use of passive safety systems in order to ensure safe rapid shutdown and long-term cooling in case of a station blackout. [40] Additionally, the modular reactor systems allow more extensive offsite manufacturing, which may reduce costs and mistakes in installation. [14]

NuScale Power has not yet filed for a design certification with the NRC, so approval of this reactor concept for construction is not likely to be feasible for at least four more years [40]. However, of all the extant SMR designs NuScales is the closest to actual licensing; therefore, it was chosen as the representative for small reactors for this study.

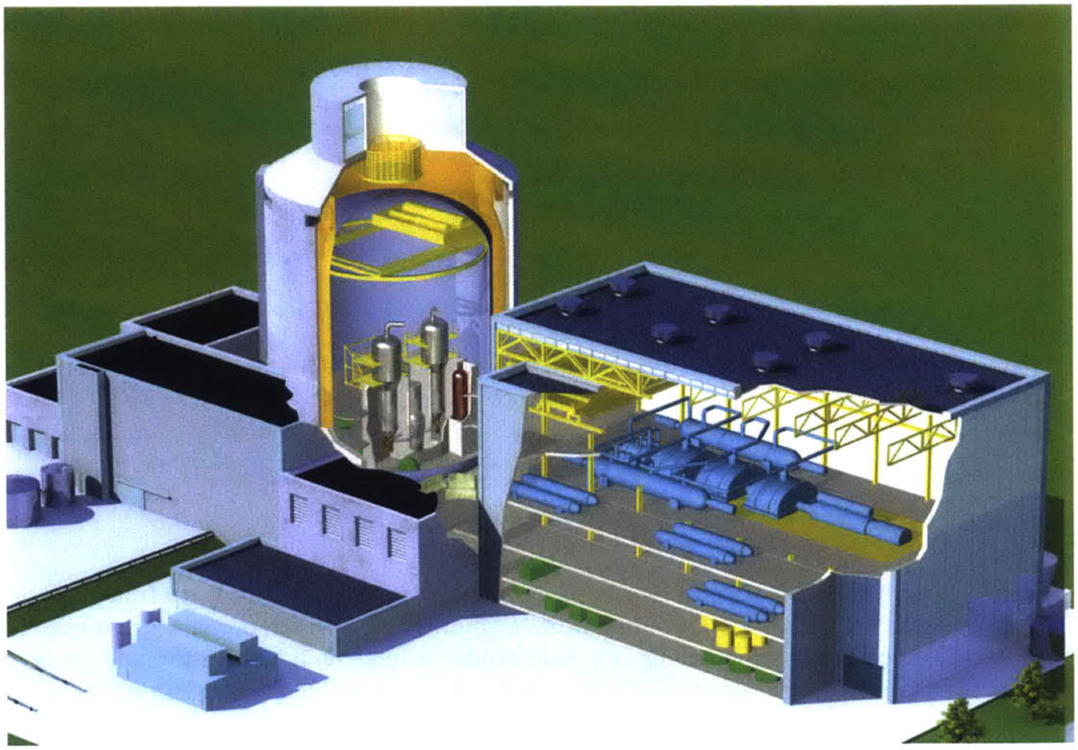

Figure 2: Rendition of the AP1000 reactor plant. The silo-like building on the left houses the reactor and containment; the rectangular building on the right houses the turbine-generators. Image source: Westinghouse.

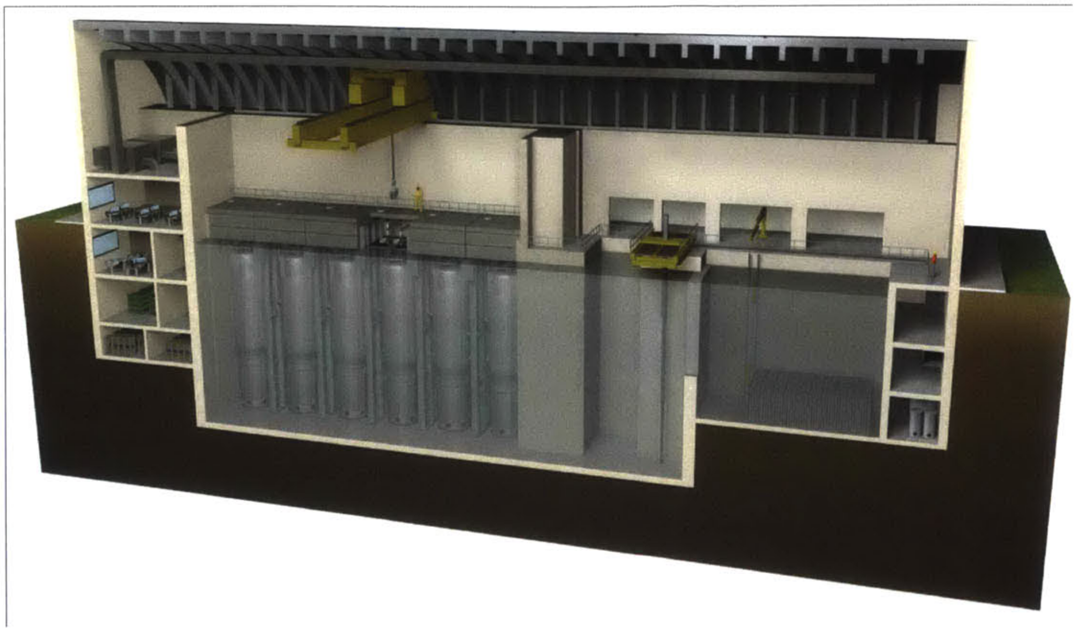

Figure 3: Rendition of the NuScale SMR reactor plant. The reactor modules are kept below-ground, with the reactors themselves constantly immersed in a large pool of water. Each module has its own "nook," and all modules operate independently from one another. The empty nook on the right is the servicing station. Image source: NuScale Power.

6.2.2 NuScale SMR Economic Strategy

The NuScale SMR, because it is small, can offer a much lower total up-front cost than the AP1000 can. Although a minimum- or medium- size NuScale power station may have interesting economic implications, for this study, a fully built out 12-module plant was assumed. However, it is less fuel-efficient and costs more per kilowatt to build. [14]

7 Parameter Selection

7.1 Reactor Specifications

Estimates for overnight cost, operation and maintenance costs, fuel costs, and nominal lead times were obtained from vendor publications for the AP1000 [37] [41] and for the NuScale SMR [14]. Costs are reported below on an annual basis for clarity.

Attribute	**AP1000**	**NuScale SMR**
Overnight cost ($, 2015)	5.227e9	2.742e9
Nominal lead time (years)	6	4
Capacity (MWe)	1117	540
O&M Cost ($ / year, 2015)	171.236e6	108.799e6
Fuel Cost ($ / year, 2015)	54e6	66.225e6

Table 1: Reactor specs.

7.2 Delay Multipliers

Detailed lead time and schedule change information was available for 76 individual reactor projects from the 1986 EIA report "An Analysis of Nuclear Power Construction Costs" [3]. This report provided the initial construction lead time estimate and the actual final construction time; this data was used to calculate a delay multiplier for each of the projects. MATLAB was used to calculate the delay multipliers at the 5th, 50th, and 95th percentiles of the data. These were used to represent optimistic, median, and pessimistic cases for actual delay. In the model, these factors multiply the estimated lead time for the reactor to get the actual lead time.

Case	**Percentile**	**Multiplier**
Optimistic	5th	1.2006
Median	50th	1.8333
Pessimistic	95th	3.3855

Table 2: Delay multipliers.

7.3 Utility Credit Ratings

A recent report from the Edison Electric Institute [42] contains a breakdown of the credit scores for electric utility companies in the US from Standard & Poor. According to the report, the distribution is as follows:

Credit Rating	Percentage of utilities
Below BBB-	4%
BBB-	8%
BBB	34%
BBB+	28%
A-	23%
A or higher	4%

Table 3: Credit ratings.

This analysis will include six credit rating categories, one for each of the above entries. The "Below BBB-" category will be represented by BB, and the 'A or higher' category will be represented by A.

Additionally, past experience has shown that nuclear investments tend to induce credit downgrades in utility companies by an average of four notches. This effect may occur before, during, or after construction of a new nuclear plant [7]. For example, both Georgia Power and SCANA (South Carolina's regulated utility) were downgraded or put on watch by Moody's Investors Service after the announcement of their intentions to build new AP1000 power plants [46] [47]. However, the smaller financial magnitude of SMR projects may insulate utilities from this effect to some extent.

7.4 Cost of Debt

New York University's Stern School of Business has extracted expected credit spreads on debt for a variety of industries, including the electric power industry [44] from available credit data. These spreads are listed below. The final cost of debt used for each case is the risk-free rate plus the credit spread. The U.S. Treasury bond rate used as the risk-free rate is 2.7%/year (value retrieved from the U.S. Treasury website on 4 May 2015 [45]).

Credit rating	Credit spread	Cost of debt
BB	2.91%	5.61%
BBB	1.31%	4.01%
A	1.09%	3.79%

Table 4: Costs of debt.

7.5 Cost of Equity

The Division of Ratepayer Advocates (DRA) for the California Public Utilities Commission uses an 8.5% return on equity at a rating of A-, with a .25% penalty for each notch lower than A-, asserting that this difference "reflects the typical difference between the yields for different bond rating categories" [43]. This approach will be used in MEERKAT. The costs of equity to be used in this model are shown below.

Credit rating	Cost of Equity
BB	9.5%
BBB-	9.25%
BBB	9.0%
BBB+	8.75%
A-	8.5%
A	8.25%

Table 5: Costs of equity.

7.6 Weighted Average Cost of Capital (WACC)

In this study, a 50/50 debt/equity split has been assumed. Therefore, the WACC is the simple average of the cost of debt and the cost of equity for each credit rating category.

Credit rating	WACC
BB	7.56%
BBB-	6.63%
BBB	6.505%
BBB+	6.38%
A-	6.145%
A	6.02%

Table 6: Weighted average costs of capital.

7.7 Minor Parameters

A number of parameters are required to fill out the cost estimate, the effects of which are not being particularly examined here.

Reactor lifetime	40 years
Loan repayment term	20 years
Discount rate	3%/year
Inflation rate	2%/year
Fuel cost escalation rate	0.5%/year
O&M cost escalation rate	1%/year

Table 7: Minor parameters.

Reactor lifetime has been assumed to be 40 years, despite the possibility that new reactors would operate for 60 years. This is simply a conservative assumption.

The inflation rate is the average rate for the 2010-2014 period, as taken from the U.S. Bureau of Labor Statistics [48].

The escalation rates are borrowed from the 2003 MIT "Future of Nuclear Power" study. Extensive research has not been done into the accuracy of these rates, but their effect is very minor.

8 The Model

8.1 Purpose of the Model

MEERKAT iteratively generates 36 project scenarios across three parameter spaces: reactor type, project delay, and utility credit rating. For each scenario, it evaluates the total construction cost and the LCOE required to pay back the project's investment and operation costs. These values can be compared to one another and to representative prices for various markets in the US in order to determine under what circumstances a nuclear project might be justifiable.

8.2 MEERKAT

For each parameter set, MEERKAT calculates the total construction cost, assuming that expenditures follow a half-period sinusoidal pattern (nearly zero at the beginning, highest at the halfway point, nearly zero at the end). Interest and inflation are added for each month, and the resulting series of outlays is summed to get the total construction cost.

To simplify the results, the LCOE is calculated for the first year of operation only, since year-by-year changes in this value can be recreated from the first-year value with the appropriate interest and escalation terms. The LCOE is calculated as follows:

$$\text{LCOE} = \frac{\Big((\text{O\&M}) \cdot (1+e_{om})^{lead} + (\text{fuel cost}) \cdot (1+e_{fuel})^{\text{lead}} \cdot \text{CF} + (\text{loan payment})\Big) \cdot (1+f)^{lead}}{\text{MW} \cdot \text{CF} \cdot 10 \cdot 8760} \tag{2}$$

where:

- *O&M* is the operation and maintenance cost in \$/yr;
- e_{om} is the escalation rate for O&M in %/yr;
- *lead* is the total lead time of the project in years;
- *fuel cost* is in \$/yr;
- *CF* is the capacity factor for the project;
- *loan payment* is in \$/yr;
- MW is the capacity of the plant in MW;
- 10 is the conversion from \$/MW to cents/kW; and
- 8760 is the number of hours in a year, to convert from cents/kW to cents/kWh.

The loan payment is calculated with the capital recovery factor for equal loan payments:

$$\text{loan payment} = (\text{Construction cost}) \left[\frac{r(1+r)^{term}}{(1+r)^{term}-1}\right] \tag{3}$$

where r is the scenario's WACC in %/yr, and *term* is the time to maturity of the construction loan in years.

9 Results and Discussion

The results from MEERKAT are discussed below. The scenarios have been split up into three categories by delay case.

9.1 Benchmark Electricity Prices

To provide context for the LCOE values produced by MEERKAT, actual electricity prices from the U.S. Energy Information Administration for various regions of the US have been compiled here. These data are averages for 2014, in order to exclude the distorting effects on price and demand caused by the anomalously cold 2014-2015 winter in many areas.

Restructured Region/Market	**Electricity price, cents/kWh** [49]
PJM (PA, NJ, MD)	6.35
CAISO (CA)	5.27
New England	7.625
ERCOT (TX)	4.16

Table 8: Electricity prices for restructured markets (2014 average).

Regulated State	**Electricity price, cents/kWh [50]**
Georgia	9.83
Arizona	10.02
Vermont	14.60
Michigan	11.09

Table 9: Electricity prices for regulated markets (2014 average).

In restructured markets, the utilities only engage in generation, so the costs of moving power, maintaining power lines and conversion infrastructure, and demand-side activities are omitted. This *wholesale* price reflects the true average cost of generating electricity in that region.

The regulated-market prices are higher because the utility performs all the functions of a vertically-integrated power company: generation, transmission, and distribution. When considering whether a new plant would be profitable in a market, the regulated-market prices are therefore artificially high, since the profits must pay for non-generation activities. However, wholesale price data for these markets are not generally available (such a price would be fictitious, since the utility does not sell the power until the retail stage). Therefore, *retail* price data have been listed to provide a general sense of power prices in the region. Regulated utilities also have the benefit of being able to request higher electricity rates to support certain projects from their regional Public Utility Commission through a rate case, although these rates may not be granted.

9.2 Optimistic Delay Case

In the optimistic delay case, the AP1000 is cheaper than the SMR by about 1 cent/kWh across all credit ratings. Even in this best-case scenario, all LCOEs are well above the wholesale power prices in deregulated markets. However, in the regulated markets, these prices are lower than (or within reasonable range of) the actual market prices. Especially for a utility with a high credit rating, building either an AP1000 or an SMR could be a justifiable business decision if the utility is confident that delays will be short.

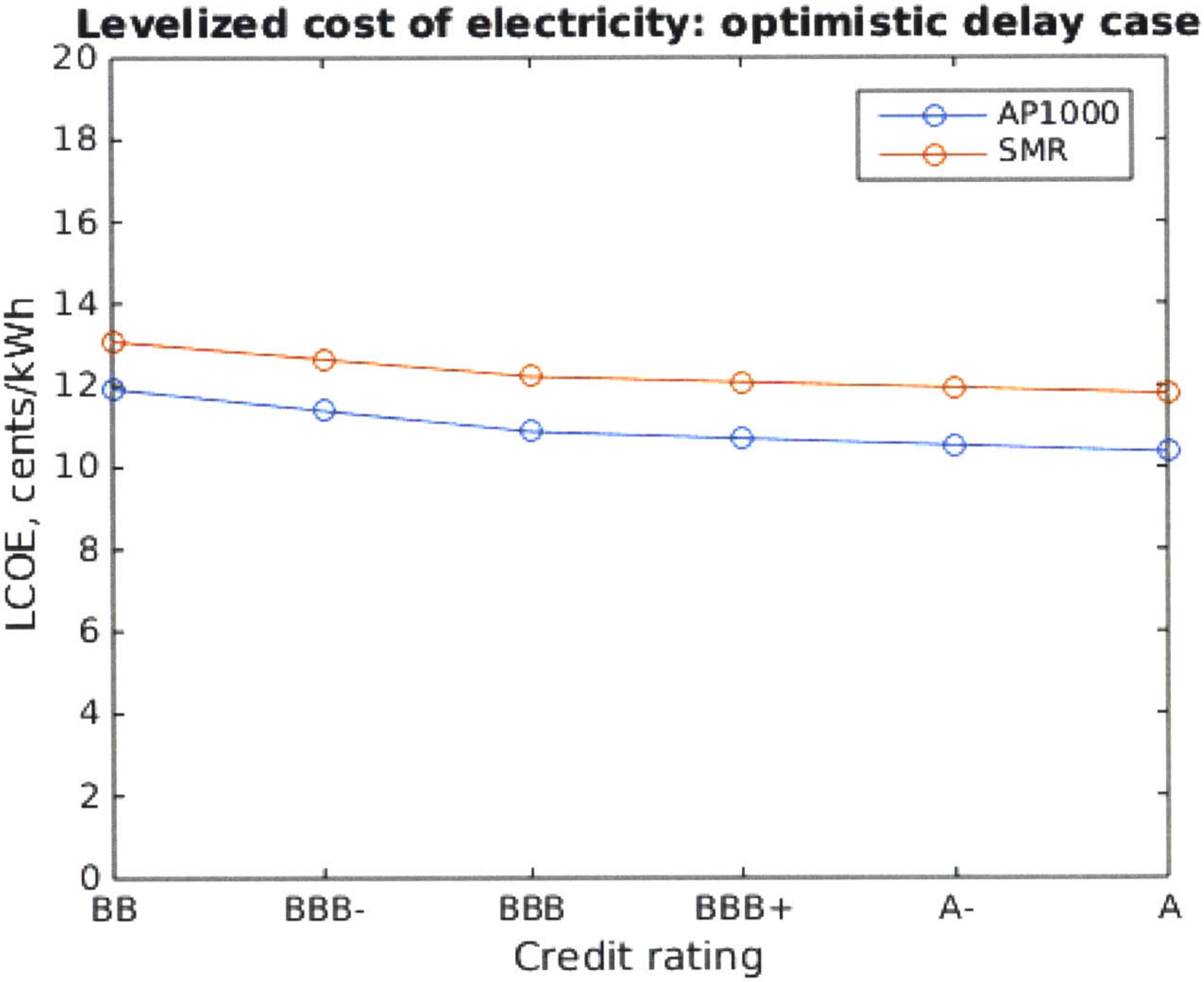

Figure 4: Levelized cost of electricity in the optimistic delay case (schedule multiplier = 1.2006).

9.3 Median Delay Case

In the median case, the SMR approaches the AP1000 more closely in price, but all prices move up by 2-3 cents/kWh. These prices are almost all higher than both the deregulated-market and regulated-market prices. If the utility has a high enough credit rating it might be able to make a case for a nuclear project in a high-cost regulated market even if it expects delay to be in line with the median of historical experience. However, the commercialization case here is clearly much weaker than for the short-delay case.

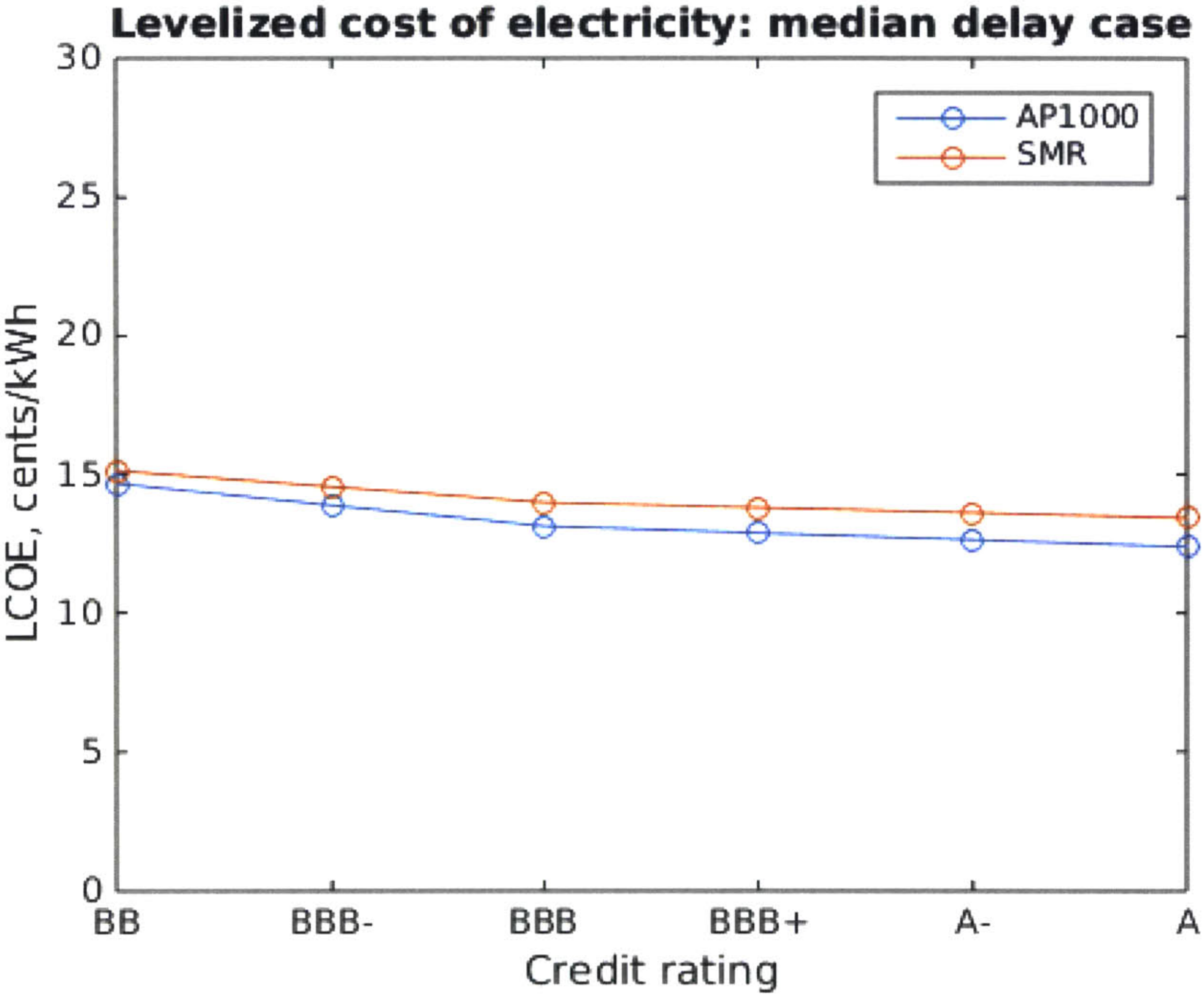

Figure 5: Levelized cost of electricity in the median delay case (schedule multiplier = 1.8333).

9.4 Pessimistic Delay Case

Figure 6 shows the scenario results in the pessimistic delay case, where construction takes 3.3855 times as long as expected. In the pessimistic case, the SMR wins out over the AP1000 by a significant margin. However, in all cases the LCOE is several times higher than all of the reference power prices in the deregulated market, and significantly larger than any regulated-market price. Regardless of the parent utility's credit rating, any AP1000 or NuScale SMR project expected to experience delay of this type is unjustifiable.

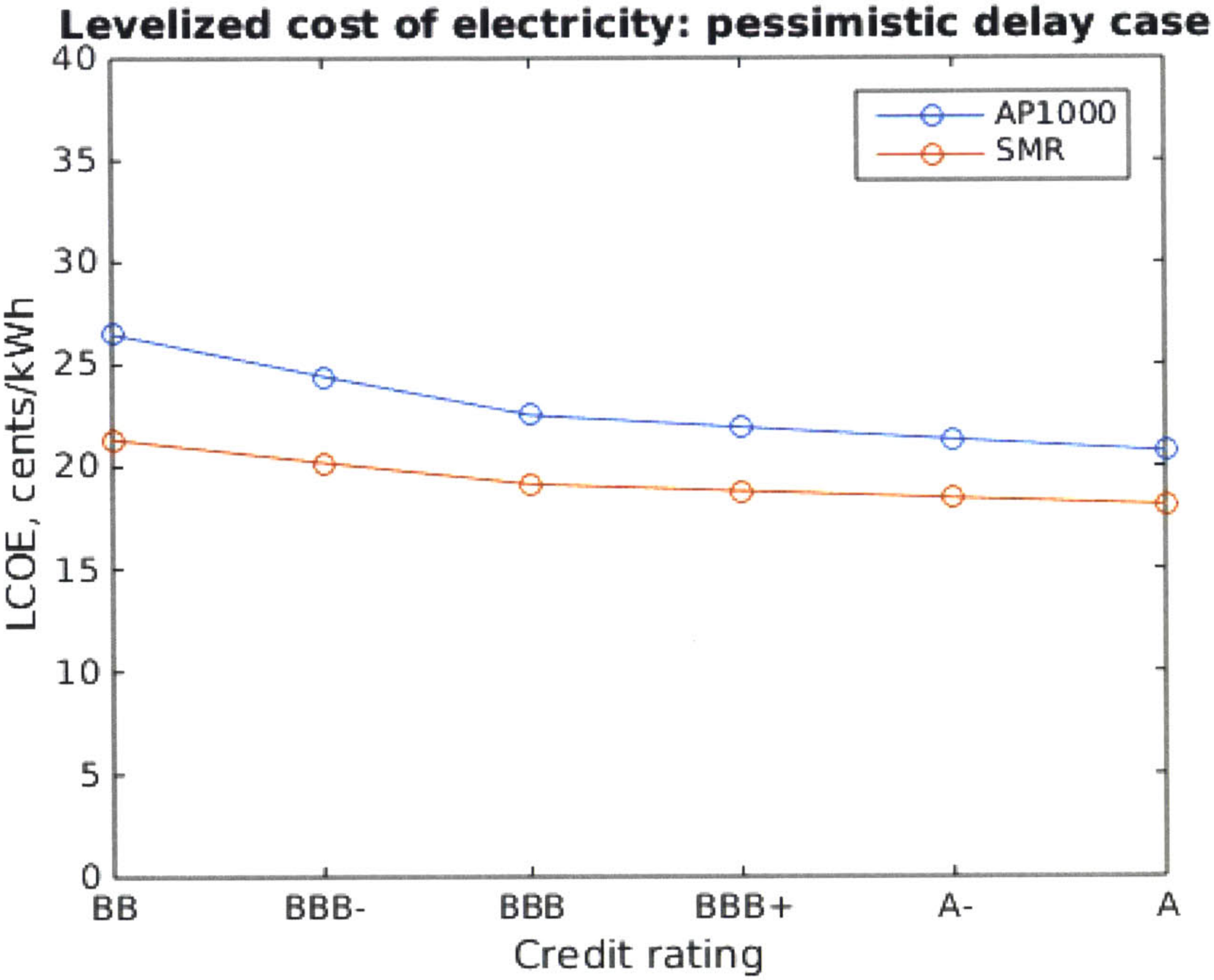

Figure 6: Levelized cost of electricity in the median delay case (schedule multiplier = 3.3855).

9.5 Comparison to MIT and UChicago Results

The MIT Update on the Cost of Nuclear Power produced LCOE estimates of 9.9 cents/kWh and 7.7 cents/kWh in 2015 terms. The UChicago reported LCOE estimates of 7.0 cents/kWh and 8.1 cents/kWh. All of these values are lower than even the most optimistic case (the short-delay AP1000 with an A-rated utility). This difference can be attributed mostly to the increase in overnight cost estimates following these studies' publication, as well as to different methodologies for calculating the cost of capital.

9.6 Total Construction Costs

9.6.1 Differential Credit-rating Stresses

An additional important consideration is the total realized construction cost (KC), which is equivalent to the total amount of the construction loan at the time the plant enters service. Figure 7 shows the total KC for each scenario (all plotted on the same axes to avoid an overabundance of graphs). The delay-multiplier bins are ticked along the x-axis, and each bin contains the six credit-rating entries, which increase from left to right within each delay bin.

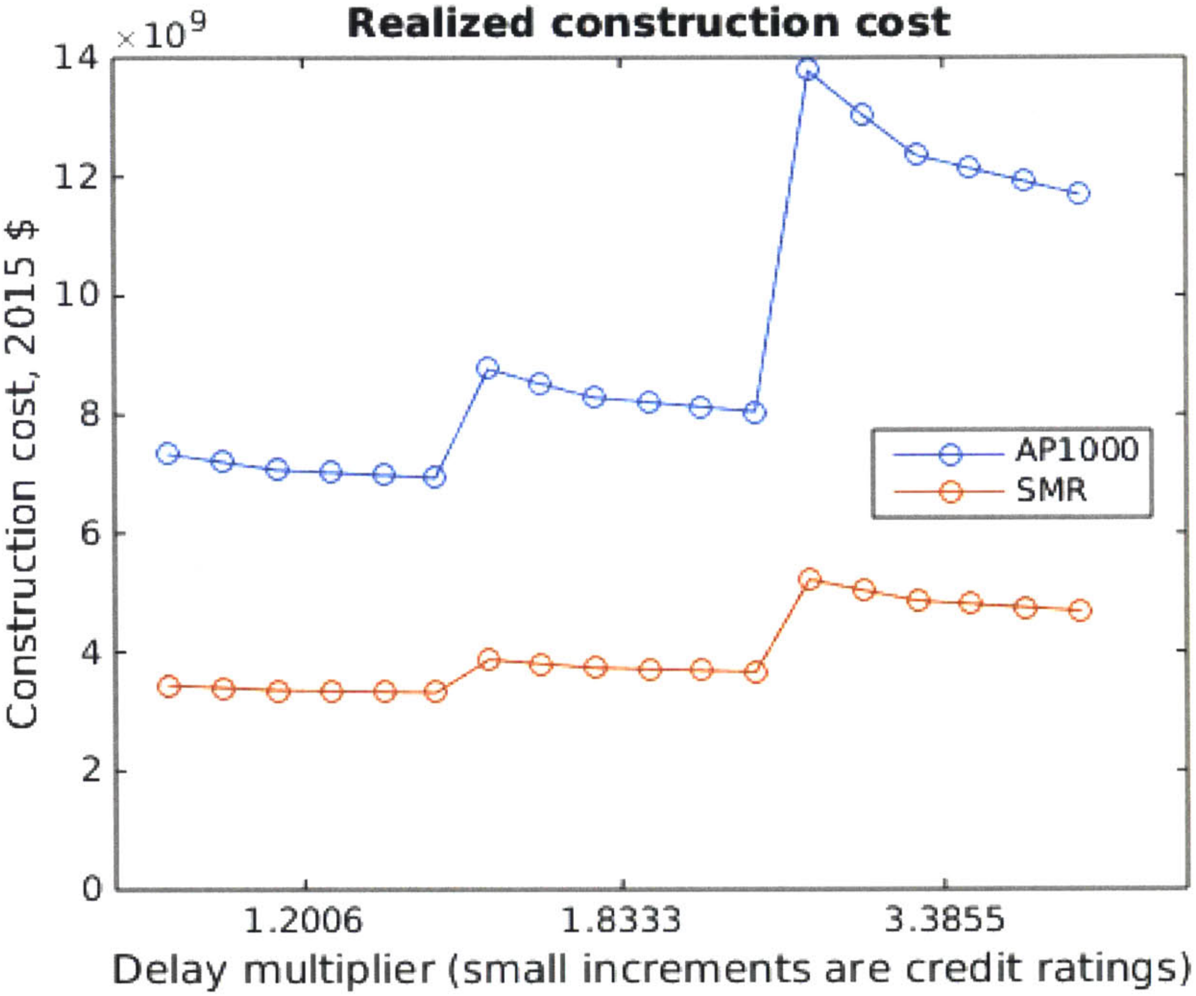

Figure 7: Total construction cost for each scenario. There are six points for each delay multiplier, representing scenario outcomes under the progression of credit ratings (BB, BBB-, BBB, BBB+, A-, and A).

One effect that is not accounted for in the LCOE analysis is the absolute magnitude of the escalation risk associated with each reactor type. As can be see in Figure 7, the AP1000 nearly doubles in cost from the low-delay to high-delay case, resulting in an overexpenditure between $5 billion and $7 billion. The worst escalation in the SMR case is less than $2 billion. Either overexpenditure case would clearly be problematic for the utility, but in the AP1000 case that unexpected $5-7 billion in loan debt could seriously damage the financial metrics and solvency of the company.

It is this heavy debt burden from both expected and unexpected construction costs that causes Moody's Investors Service and other ratings agencies to "view new nuclear generation plans as a 'bet the farm' endeavor for most companies" [7]. Therefore, the AP1000 project may have more significant negative impacts on the parent utility's credit rating than the less-costly SMR, resulting in higher costs of capital for the AP1000. As previously noted, credit-rating downgrades can be preemptive upon the announcement of a company's intentions to pursue a nuclear project, so the negative perception of the project may impact the project's own cost of capital.

One way to explore this possibility is to compare AP1000 and SMR projects at a credit-rating offset. Historically, nuclear projects caused the average utility to be downgraded by four notches (i.e. A to A- to BBB+ to BBB to BBB-) [7]. Because the SMR is less expensive and its cost overruns are proportionally smaller in magnitude, the financial and credit stresses it would place on a company are also likely to be smaller. To illustrate, the LCOE for AP1000 and SMR projects has been plotted assuming a one-notch fictitious "credit penalty" to the AP1000 project.

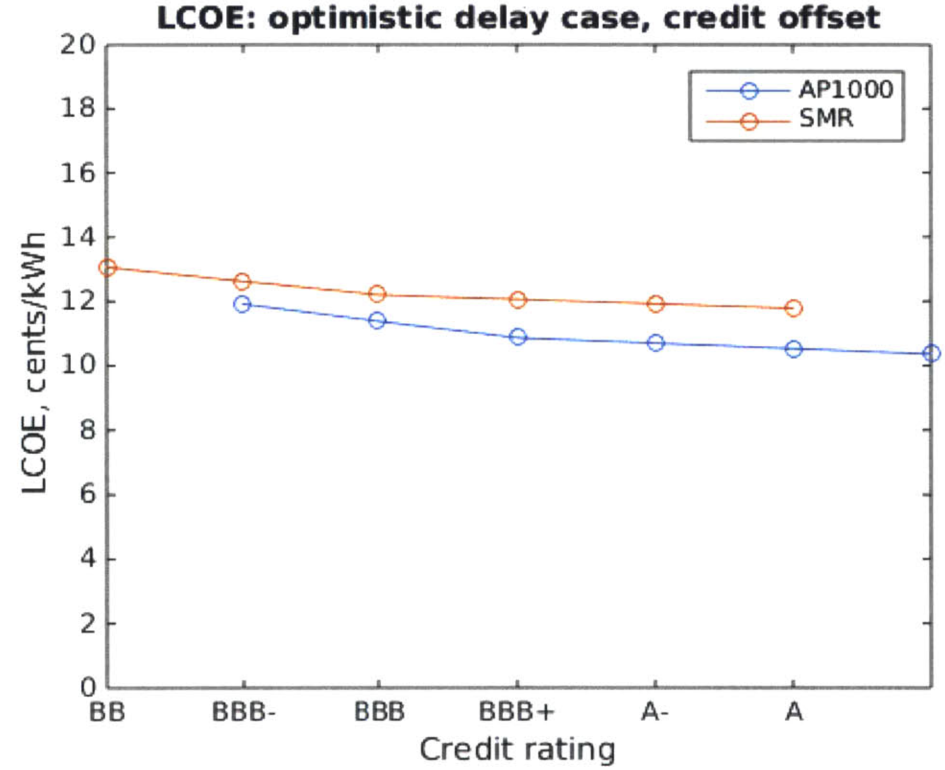

Figure 8: LCOE of AP1000 and SMR projects in the optimistic delay case, with the AP1000 values offset by one credit-rating notch to simulate the greater strain placed on the utility's rating.

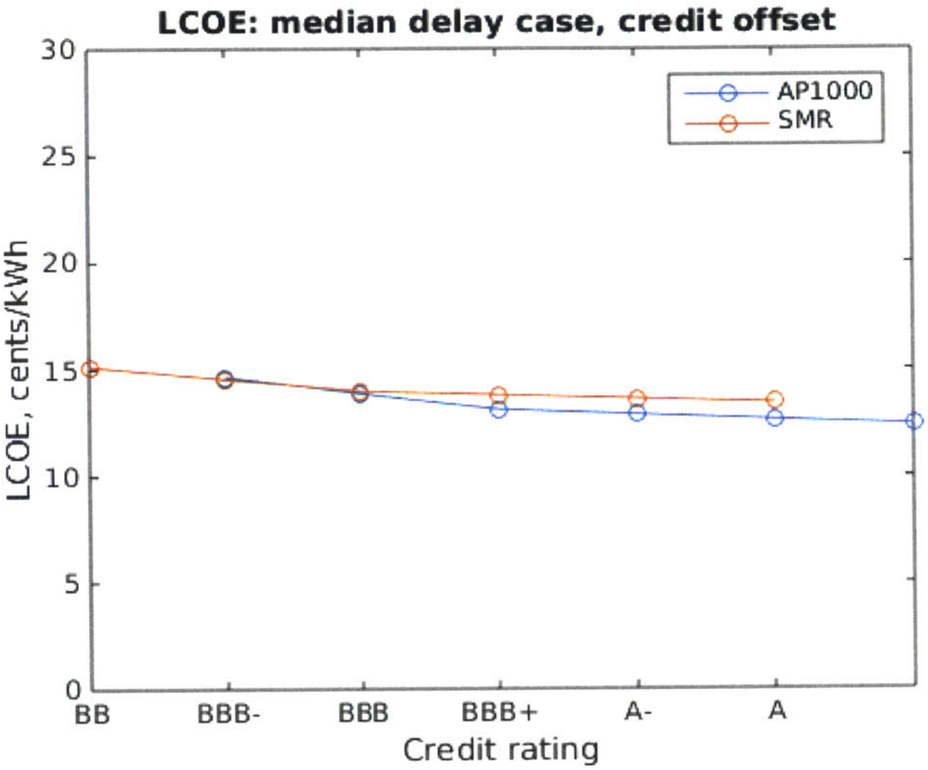

Figure 9: LCOE of AP1000 and SMR projects in the median delay case, with the AP1000 values offset by one credit-rating notch to simulate the greater strain placed on the utility's rating.

The effect for the pessimistic delay case was negligible, so the results of this adjustment have been omitted for that case.

However, in the optimistic and median cases, this one-notch shift notably improves the performance of the SMR relative to the AP1000. Figure 8 shows that the margin by which the AP1000 beats the SMR is diminished in the optimistic delay scenarios. In Figure 9 the results are even more significantly affected, with the SMR actually producing near-identical LCOEs versus the AP1000 for two scenarios. Nevertheless, the credit offset does not change the performance of either reactor type relative to the market as a whole.

If a greater offset were used, this effect would be amplified. However, without more quantitative information on how each project would affect credit ratings, it is impossible to justify a specific credit offset to be used. This effect is qualitative, although certainly important, as 40 years of nuclear construction and finance history can attest [7].

9.6.2 Potential Customer Base

The available financial resources of the utility engaging in a new nuclear build may have great significance in its planners' decisions on which nuclear technology to pursue. Two thirds of the electricity generated in the US comes from utilities with an annual revenue less than \$2.527 billion, a figure which does not account for operational costs and other liabilities [51]; actual net income is much smaller, under 10% of revenues on average. In the most optimistic AP1000 case, the amount that must be recouped from electricity sales is \$933 million each year. Essentially, this 67th-percentile utility must increase its revenue stream by 37% in a single bound in order to pay the financing and operating costs of the AP1000, and this figure only increases as the scenario moves away from the best possible assumptions. For larger utilities this requirement is not quite so severe, but given the slow rate of electricity demand growth in recent years [54], there are few opportunities for any utility to unilaterally recoup such a large revenue from its market.

On the other hand, in the most optimistic SMR case, the annual cost to be recouped is \$513 million. The 67th-percentile utility from the previous example must be able to secure a revenue increase of 20%; still a hefty amount, but perhaps a more realistic goal. By virtue of this significant difference in financial scale, the SMR is a feasible project for a wider cross-section of the electric power industry than the AP1000.

If, as is posited in the previous section, the SMR also provides benefits by insulating companies against nuclear-related credit downgrades, the SMR may offer significant financial benefits that are masked by the pure LCOE analysis.

10 Conclusions

The purpose of this research was to compare the economic viability of the AP1000 and the NuScale SMR under diverse conditions. A variety of project delay cases and company credit ratings have been considered.

10.1 Levelized cost of electricity

No scenario produced a levelized cost of electricity low enough to create a compelling commercialization case. Even under the most optimistic of conditions, nuclear power is financially unfeasible in a competitive, restructured electricity market. Under the optimistic delay case and the higher credit ratings, either reactor type could be justifiable in a regulated market, with the AP1000 faring slightly better than the SMR. However, the LCOEs even in these best-case scenarios are on the upper end for regulated markets. If a credit offset is incorporated into the analysis, the SMR becomes more competitive with the AP1000, but neither reactor becomes more competitive relative to the market as a whole.

In the median, more probable delay case, a highly-rated regulated utility may be able to justify building an AP1000 or an SMR if it resides in an already-expensive market. If a credit offset is used, the SMR becomes much more competitive with the AP1000, but the LCOEs for all projects are still high relative to extant market prices.

In the pessimistic case, no construction scenario makes economic sense, with or without the credit-rating offset.

10.2 Total construction cost

The AP1000 poses a formidable up-front cost barrier. A utility must shoulder a great deal of debt in order to build one, and the consequences of delay-related cost increases are much greater in magnitude for the AP1000 than for the SMR. Additionally, the AP1000's large capital cost limits potential customers to the largest utility companies in the US, whereas the SMR's lower up-front cost may allow smaller utilities to construct them.

11 Limitations and Future Work

Cost estimation for complex projects like nuclear reactors is a complicated process with many confounding factors. Many of these factors are poorly understood, lack empirical data, or have an unclear level of influence on the final cost. This study has included all factors for which there was sufficient empirical or theoretical support; following is an enumeration of some of the factors that were excluded, but which may have a significant impact on the cost of nuclear power.

11.1 Risk Premium for Nuclear

While the cost of capital for a nuclear power plant construction project may be reasonably estimated from factors applying generally to all utility construction, there is evidence that a higher cost of capital may be required a priori for nuclear investments. Moodys Investors Service has stated that they "considering taking a more explicitly negative view of nuclear". More explicit data on the ramifications of this position has yet to be released, but the statement reflects a more general view that nuclear investments are inherently more risky than investments in other types of generation, and this limitation should be kept in mind when attempting to predict interest rates.

11.2 Loan Guarantees

The Department of Energy offers a loan guarantee program for utility companies seeking to build new nuclear power plants [53]. A loan guarantee is a promise by an external agency to pay for a company's loan obligations in the case that the company defaults. This reduces the risks faced by investors, particularly on projects like nuclear builds which are perceived as prone to cancellation and default, and therefore reduces the costs of both debt and equity. The effect of a loan guarantee can be difficult to quantify and has not been included here.

11.3 Comparison to Competing Technologies

This investigation concludes that SMRs are more appropriate for a variety of deployment scenarios. The larger question at hand, of course, is whether SMRs are the most appropriate power-generation technology in those cases, which this research does not address. Combined-cycle gas turbines are currently the fastest-growing electricity generator type, but a thorough investigation on this front should also compare SMRs to single-cycle gas turbines, coal power, and possibly renewable technologies.

Additionally, because nuclear power is a zero-carbon energy technology, the institution of a price for carbon would increase its economic competitiveness relative to coal and gas power. Various types of carbon pricing have been proposed, although none have been instituted on a national scale. It may be of value to expand this research to include consideration of the effects of carbon pricing, if competing technologies are also to be taken into account.

11.4 Demand Growth Risk

In the heyday of nuclear construction, about half of the nuclear power plant construction projects that were seriously announced were cancelled. In the majority of cancellations, lower-than-expected electricity demand growth was listed as a major factor driving the cancellation. This disparity was due to the poor performance of demand prediction models, as well as unpredictable dips in demand growth due to national and global economic events. Over time, growth in electricity demand has slowed (from 9%/yr in 1958 to 1%/yr in 2012 [54]), making prediction easier and narrowing the distribution of probable actualized load values, but this risk is still present.

Demand uncertainty affects all generation projects; however, it will create more risk in large projects than small ones. One important case in which demand-related risk can be avoided is when replacing an existing power plant that is scheduled for retirement. Considering that a number of aging coal plants are nearing their mandated retirement date, this deployment case may present an important opportunity for nuclear.

There is little extant research on the effects of demand-growth uncertainty on the financing of power projects; most sources list it as a qualitative effect, or claim that the smaller demand growth in recent years has rendered the related risk a minor quantity.

11.5 Representativeness of Historical Data

This analysis makes use of data on 76 reactor construction projects completed in the US between 1967 and 1986 [3]. This is a fairly large subsection of the 110 completed nuclear reactors in the US; data acquisition was curtailed by nonstandard or nonexistent project data reporting procedures for much of the time period in question. Additionally, the usefulness of this data may be limited by institutional changes in the practices used by the construction and utility industries in the intervening years between the height of reactor construction and the present day. Therefore, the values used for delay multipliers should be understood as the best available estimates, given the lack of more recent and extensive data.

11.6 Quantitative Treatment of Market Structure

Financially, the fundamental difference between traditionally-regulated and restructured electricity markets is in its agents tolerance of risk. There is currently little extant research to support quantitative assertions about the level of risk or cost of capital that a firm in either market type would accept, beyond the intuitive understanding that such acceptance will be higher in the traditional market than in the restructured one, due to additional uncertainty about the actions of competing firms. Further research in this vein is required before market structure can be incorporated numerically into the model.

11.7 Construction Escalation

Construction materials, labor, and associated costs typically increase over time at a rate that cannot be fully accounted for by inflation. This real cost increase is referred to as *escalation*. It has not been included here because the exact values are not well-characterized, and because escalation is a relatively minor factor.

12 Glossary

capital project In this document, "capital project" is used to refer to a project that requires a large up-front investment and a long development period before it can generate revenue.

credit rating A rating issued by one of the three major credit-ratings firms (Moody's, Standard & Poor, or Fitch) that indicates the creditworthiness of a company. A high credit rating indicates a sound investment with low risk of default; a low credit rating indicates a poor investment with high risk of default. Companies with a lower credit rating will have access to less capital, and the capital they borrow will come with a higher interest rate. Utility credit ratings take into account company revenues, amount of outstanding debt, diversity of generating portfolio, regulatory regime, market outlooks, and several other factors.

credit spread The extra premium charged, on top of the U.S. Treasury Bond rate, to a utility with a certain credit rating. Credit spread increases as credit rating decreases.

debt Money owed to a lending institution such as a bank.

default The act of reneging on a loan agreement. If a borrower defaults on a loan, the lender may be repaid all, some, or none of their investment, depending on the assets of the borrower and the terms of the loan.

equity Money owed to a company's own stakeholders.

escalation Cost increase over time. Can be the result of interest accumulation or real cost increases (material/labor).

lead time The time span of construction, usually defined to be between the first concrete pour and connection to the grid.

levelized cost of electricity (LCOE) The price that must be charged for power in order to cover all of a plant's costs, including construction loan payments, operation and maintenance costs, and fuel costs.

rate case An appeal made by a regulated utility to its regulatory body, which usually requests a certain electricity price with supporting details about company operating and debt-servicing costs.

regulated market An electricity market in which one company holds a monopoly on all electricity-provision services (generation, transmission, distribution, and retail). These companies are regulated by a dedicated regional Public Service Commission and submit rate cases to request remuneration for their services.

restructured market An electricity market in which generation, distribution, retail, or some combination of those are provided by free-market actors. Also called a *deregulated* market.

retail price The price paid by end consumers of electricity. Regulated utilities, and distribution companies operating in deregulated markets, use this price.

risk-free rate An investor desiring a zero-risk investment can invest in U.S. Treasury bonds, which have essentially zero risk of default. The rate of these returns is commensurately lower than the rate available on riskier investments. This value is available from the U.S. Treasury website.

weighted average cost of capital (WACC) The weighted average of the interest rate on debt and the interest rate on equity.

wholesale price The price bid by a generating utility on a power exchange, which is paid by a separate distribution company. Relevant only to restructured markets.

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