Uncertainty, Policy, and the Risk of New Nuclear Build—a Real Options Approach

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Abstract

Policy incentives from the Energy Policy Act of 2005 and substantial changes to the Nuclear Regulatory Commission's licensing process have led to a recent surge in interest in new nuclear power plant construction in the United States. However, the new licensing processes are untested and the new reactor designs have never been constructed on US soil. Analyzing the history of US nuclear development demonstrates that plants face considerable risk from construction uncertainties, public intervention in the licensing process, and project mismanagement. When these unknowns are coupled with the industry's poor cost track record, the resulting set of uncertainties and risks may cause investors to be wary of pursuing new nuclear projects.

Real Options valuation was used to assess how the risks associated with the uncertainties in the environment for nuclear power could impact the economics of new plants. To value a new nuclear power plant a decision model was developed incorporating construction, regulatory, and operational uncertainties along with an option to abandon project development. Various policy and uncertainty scenarios were modeled and a conservative policy goal was developed as an achievable end point for the current levels of subsidy.

The results suggest that without subsidy, the first new plants in the United States are economically unattractive in liberalized electricity markets. Subsidized plants have positive investment value, but this value, only $7 per kilowatt, is still marginal. However, cost reductions from standardization and learning could add between $200 and $600 per kilowatt in project value. Additionally, alternative incentive policies and market-based greenhouse gas regulations both considerably improve the economics of new nuclear plants.

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Contents

1 Introduction

1.1 A Nuclear Renaissance?

Starting in the 1980s, it appeared as though the US nuclear industry would never recover from its regulatory assisted suicide, a period of intense public opposition, out-of-control cost increases, and a spate of poor management decisions which seemed to permanently sully the industry's reputation. Yet, the first decade of the 21st century has brought substantial change to the landscape of nuclear power. In an acknowledgement of rejuvenated interest in nuclear power plant (NPP) development, the Nuclear Regulatory Commission (NRC) has received 18 license applications for 28 new nuclear reactors (NRC, 2010). Other market participants have partially cast their lot with a new generation of reactors in the United States as uranium mining applications have risen from their own two decade graveyard (Frye Jr. 2008). This isn't necessarily an indication of exclusive support for new build—the market for existing reactors has been relatively robust with smaller regulated utilities selling off their nuclear assets to highly efficient nuclear operating companies. But, the renewed growth and interest in the nuclear industry is demonstrable. Even some in the environmental community, previously opposed to nuclear development due to concerns over waste disposal and invasive mining techniques have slowly moderated their otherwise vehement opposition to the expansion of US nuclear capacity in the face of even less palatable fossil alternatives and the challenges posed by global climate change (as an example, see Brand, 2005).

The infant renaissance is not without its stumbling blocks. The risks faced by the industry are huge—a lack of US development has atrophied the industry's professional and manufacturing support system, new reactor designs lie untested, and the new regulatory procedures have yet to prove they definitively solve the suffocating delays their reform has been intended to avoid. Risk pervades the new nuclear power industry, and risk will ultimately determine how and when investment is directed towards new NPPs, and how this investment may itself poses risks to the continued US resurgence of nuclear power.

1.2 The Role of Risk

Risk, broadly construed, is the danger posed to a system by elements of uncertainty. If one were to know with complete certainty that a negative shock would occur on a specific date, there is nothing "risky" about this shock. It can be prepared for in advance and all future plans can (again with complete certainty) incorporate this shock as a deterministic element of the future. In specific application to NPPs, risk comes in several flavors. Certain risks are internal to a project—volatility in operating costs and capacity factor for example. Others are imposed by the outside world such as higher costs of financing owing to the perceived (and historical) riskiness of nuclear investments and the fear of outside intervention by local politicians, "Not in my Back Yard" (NIMBY) activists and groups acting on environmental/social concerns.

This project is an attempt to accomplish two interrelated goals, the first is to quantitatively model the risks faced by NPP developers and then analyze how these risks interact with the investment decision to construct new NPPs. The second is to explore how the first wave of new build can eliminate or re-contextualize nuclear risk, and what implications their construction outcomes have for further NPP investment. What we are interested in is whether these risks can derail what is currently perceived as a renaissance. If this turns out to be the case,the results of this analysis can inform the development of policies for nuclear power. It is possible that targeting specific elements of risk can add considerable project value, opening more creative avenues than standard direct subsidization to incent development. Additionally, we can define a goal for these policies, demonstrating that there is a clear endpoint at which we can say they have succeeded and are no longer necessary. The components of this policy goal provide a benchmark against which to evaluate the progress realized, or unrealized, by the United States' first new wave of nuclear power plants.

I begin by detailing the history of nuclear power development in the United States in Section 2, assessing the driving forces: regulatory inadequacy, public opposition and cost escalation, which led the nuclear power industry into a period of involuntary dormancy following the Three Mile Island (TMI) accident. In section 3, I look at the changes in the past two decades which have resuscitated the prospects of US nuclear power, using this qualitative analysis to inform the development of a real-options model of NPP investor behavior. The model is outlined in section 4 (the solution procedure is described in Appendix 2, and a glossary of model notation is included in Appendix 1), and data sources and rationale for the selection of model parameters are contained in section 5. Finally, Section 6 presents the results of the model, Section 7 discusses policy options, and section 8 delves into the sensitivity of the model and its implications for NPP valuation. Section 9 leaves the reader with a handful of concluding thoughts.

2 Historical Development of Nuclear Power

2.1 <u>The Rise and Fall of the US Nuclear Industry</u>

In 1954 Congress effectively delegated all authority on the development of nuclear power to the Atomic Energy Commission (AEC), directing it to promote the development of the "peaceful atom". Through time, the AEC also became the de facto federal level regulator for nuclear power projects. This dual role, that of explicit promotion and implicit regulation, and the somewhat blatant moral hazard it implied, began to feed an infant public opposition movement (Goldsmith 1991).

The early 1970s brought the first in a damning series of regulatory changes which rippled through the nuclear industry. In 1970, the National Environmental Policy Act (NEPA) was passed and the formerly content and environmentally unaware nuclear industry was forced to begin producing highly complex, high contentious "Environmental Impact Statements" (EIS). 1974 saw the formal recognition of the potential issues caused by delegating both regulatory and promotional responsibilities to a single federal agency. Two new agencies were created out of the ruins of the AEC, the more familiar Nuclear Regulatory Commission (NRC), and the Energy Research and Development Administration (ERDA) which was to be bundled into the new Department of Energy.

Desite gradual improvement in reactor safety standards and a certain element of transparency introduced with the creation of the NRC, the potential for a serious accident remaind. This fact was not unseen at the time: the "GE three", a group of three nuclear engineers who presciently resigned over safety concerns in 1976, gave the industry and general public fair warning that the safety systems at NPPs, and subsequently the regulatory system which allowed them, were inadequate. However, it took the near complete meltdown at Three Mile Island (TMI) to generate truly substantial regulatory change. The NRC froze licensing activity for two years and by the time this freeze was lifted the nuclear industry was unable to recover from the setbacks of public opinion, regulatory failure, and escalating cost. No new reactors were started, and those which remained under construction were deeply mired in both financial and technical difficulties.

2.1.1 Public (non)Acceptance meets Regulatory Incompetence

The first of two lasting legacies of TMI (and, to a lesser extent Chernobyl) was the abrupt break point in the path of public opinion. Not surprisingly, a large, very public, and potentially very dangerous accident at a domestic nuclear facility reversed the public's opinion of the nuclear industry. Following an initial period of ambivalence immediately following TMI, public opinion swung sharply negative as the "fence sitters" came down decisively against an expansion of the nuclear power industry (Rosa and Dunlap, 1994)

Even then, public sentiment cannot, simply by existing, undermine the development of nuclear power. To prevent or delay construction of an NPP, public opposition must be channeled through some political or social institution whose influence and/or authority could undermine further nuclear development. The most direct channel for this public opposition was mass protest. The 1960s were largely devoid of public opposition, but, with popular protest movements of the 1970s buoyed by anti-war and anti-nuclear weapons sentiments, nuclear power came into the crosshairs of groups of highly organized, highly motivated activists. The first substantial, non-legalistic expression of public opposition occurred in 1977 as 20,000 demonstrators occupied the construction site of Public Service of New Hampshire's (PSNH) Seabrook nuclear generating station. This protest by the local "Clamshell Alliance" necessitated intervention by the National Guard, who arrested nearly 2000 protestors (Downey 1986). Other groups soon followed Clamshell's successful (the protesters ultimate secured their release by coordinated peaceful resistance while under detention) lead and began the use of direct protest to dely the construction of nuclear power plants.

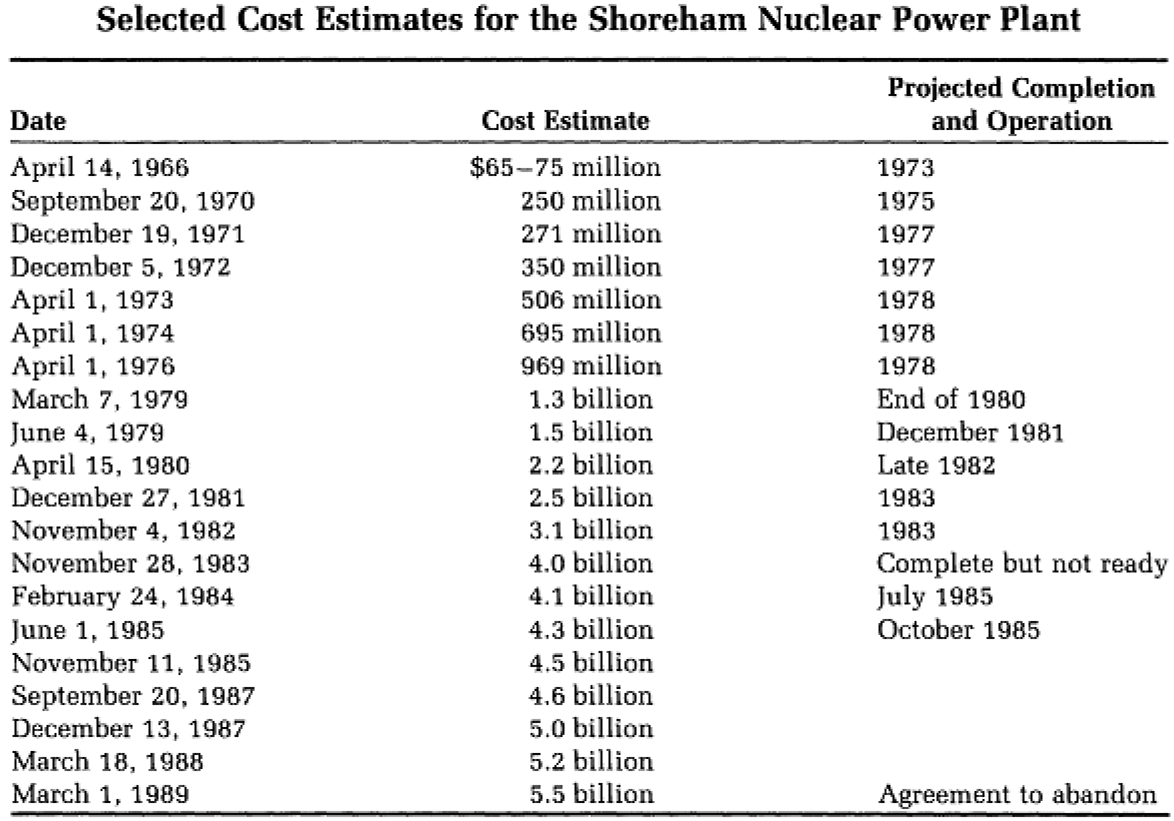
But protest was not the mechanism which ultimately brought down the industry. The Clamshell Alliance, the first, largest, and most successful of the activist movements gradually imploded, and by 1981 the group split over divisions of ideology and strategy, and never regained its public support or momentum. The efforts of the Clamshell Alliance left little lasting impact on the development path for Shoreham nuclear. While PSNH did ultimately declare bankruptcy and cancel one fot he two planned reactors, this retrenchment of activist sentiment occurred a full ten years before the utility found itself on the brink. Seabrook-1 still went into operation and the considerable protest movements of the late 1970s and early 1980s were unable to leave much of a lasting mark on the development of NPPs. Because of this organizational disintegration, Rucht (1990) argues that the anti-nuclear protest movement ultimately won, but due in no part to their own actions. It is necessary to look elsewhere to find the consequential expression and tappropriately successful channeling of anti-nuclear sentiment.

Kitschelt (1986) observes that despite low overall levels of public mobilization and a political stalemate between pro and anti-nuclear political forces in government the relatively open licensing process gave nuclear opponents an opportunity to delay construction as US courts were able to halt construction activities during licensing proceedings. Generally speaking, public opposition to NPP development was made possible through democratic channels at the state and local levels. To understand why this was possible, it is necessary to understand the purview of federal policy intervention in the context of the United State's uniquely disruptive form of federalism. The most evident form of this local intervention can be seen in the battles over NPP emergency planning measures. By the late 1970s, Congress had taken steps to essentially "decouple" the construction of a nuclear power plant from potential local and state-level government interventions by explicitly ceding all authority to the AEC, and subsequently NRC (over the state and local governments) in matters of radiological safety (Williams 1997). Buttressing this decoupling strategy was a gaping policy hole in regards to NPP safety—prior to the TMI-2 accident, utilities were not required to develop a set of emergency planning measures (outside of standard redundant design), technically called a Radiological Emergency Response Plan (RERP). The states themselves were not innocent in this gruesome regulatory oversight, largely ignoring any need for RERPs and instead relying on the judgment of federal regulators or the utility in question to determine whether an emergency response measure was necessary.

TMI necessarily exposed the need for a detailed RERP. Pennsylvania authorities had substantial difficulty evacuating the area surrounding the reactor and this failure turned the lack of RERP planning into an immediate political liability. Accordingly, In 1980 Congress required the filing of a RERP as part of the operating license issuance procedure. This legislative change opened the NPP development process to an extremely effective form of public intervention—the refusal of local authorities to sign on to utility RERP plans. The two US plants typically branded as burdensomely expensive "white elephants", Shoreham Nuclear in New York, and Seabrook Nuclear in New Hampshire, both became hopelessly mired in the operating license process specifically due to local or state authority intervention in RERP development and acceptance. Shoreham was quite literally the worst case outcome for the nuclear industry in dispute over the appropriate level of federal authority in NPP development. A particularly brutal battled raged through the federal court system, spilling into congress, and prompting intervention by both the governors of New York and Massachusetts (Dukakis was multitasking, also attempting to delay the opening of Seabrook) (Wilson 1997). The plant was completed in 1984 and Long Island Lighting Co. (LILCO) eventually canceled the completed and operating (at testing power) plant in 1989, never having sold a single kilowatt hour of electricity at a cost to NY ratepayers of 6 billion dollars. The NRC did ultimately grant the reactor it's operating license, but by that point public and institutional opposition had already dictated Shoreham's fate.

2.1.2 Escalating Costs and the Role of Mismanagement

Figure 1 - Cost Escalation through Time for the Shoreham Nuclear Project



Selected Cost Estimates for the Shoreham Nuclear Power Plant

Date	Cost Estimate	Projected Completion and Operation
April 14, 1966	$65–75 million	1973
September 20, 1970	250 million	1975
December 19, 1971	271 million	1977
December 5, 1972	350 million	1977
April 1, 1973	506 million	1978
April 1, 1974	695 million	1978
April 1, 1976	969 million	1978
March 7, 1979	1.3 billion	End of 1980
June 4, 1979	1.5 billion	December 1981
April 15, 1980	2.2 billion	Late 1982
December 27, 1981	2.5 billion	1983
November 4, 1982	3.1 billion	1983
November 28, 1983	4.0 billion	Complete but not ready
February 24, 1984	4.1 billion	July 1985
June 1, 1985	4.3 billion	October 1985
November 11, 1985	4.5 billion	
September 20, 1987	4.6 billion	
December 13, 1987	5.0 billion	
March 18, 1988	5.2 billion	
March 1, 1989	5.5 billion	Agreement to abandon

(Ross and Staw, 1993)

The second legacy of the post-TMI regulatory upheaval was the erratic and seemingly continual regulatory reform which resulted in escalating costs of construction (Pindyck, 1993). These changes on their own would have been burdensome, but questionable management decisions exacerbated what was already a clearly deteriorating environment for NPP development. The Shoreham failure is again instructive. The plant originally began construction in the early 1970s, only to be redesigned at a higher capacity—during the redesign and relicensing process, the promulgation of new regulations forced extremely costly delays and design changes. It is clear from the pattern of cost escalation that it would have been economically rational to abandon plant construction well before the RERP contention became an issue. Figure 1, taken from Ross and Staw (1993), a study of organizational escalation and lock-in, demonstrates the exponential growth in expected costs that LILCO faced throughout the 1970s and 1980s. They identify three sets of factors which drive decision makers off of economically optimal paths: Project, Psychological, and Organizational. Briefly distilling their findings: in the case of Shoreham, organizational lock-in due to a regard for sunk costs, very public reputational commitments, and irrationally optimistic outlooks of the future spurred LILCO management to make a continuous set of poor decisions. The culmination of this organizational dysfunction was the 1985 first fuel load of the reactor for low power testing. By loading the fuel roads, LILCO irradiated the reactor vessel and instantly added $200 million in exit costs to decommission the then active NPP, forcing their hand and beginning the five year RERP saga which ultimately led to the plant’s closure and decommissioning.

The decision path at Shoreham, while the single worst possible example of organizational lock-in during NPP development, was repeated to a lesser extent throughout the nuclear industry. As an example, Seabrook nuclear was originally designed to house two reactors but the second was not canceled until PSNH's bankruptcy despite great delays in their ability to obtain an operating licensing for the first Seabrook unit, skyrocketing costs, and a substantial drop in electricity demand following the 1970s oil shocks.

Taken collectively, a complex, but coherent narrative of policy and management failure and systematic risk emerges from the nuclear industries expensive travails of the 1970s and 1980s:

In the 1960s, inadequate regulatory practices lulled the industry and public into a false sense of security. This public policy house of cards began to slowly tumble with a change in the character of regulation in the early 1970s—and TMI exposed the systems' serious flaws, both regulatory and technical, which the industry lacked appropriate time to adapt to.

- Combining inadequate regulation with a sprawling licensing procedure both created *more* public opposition and gave said opposition legal and regulatory levers by which to inevitably delay operation. Meanwhile, NPP development was already suffering from poor-timing in that the threat of nuclear war between the United States and USSR allowed the linkage of the robust anti-nuclear weapons movement and opposition to nuclear electric generation.

- This public opposition, change in regulatory character, and a lack of industry standardization sent construction costs and construction times soaring. Cost became a risk in and of itself to utilities such as PSNH and LILCO.

- Poor management led to organizational lock-in, causing utilities to continue projects which, for reasons of rising cost or evaporating demand, were unnecessary and financially irrational. This drove the proverbial "nail in the coffin" of the US nuclear industry, with NPPs being branded *a priori* uneconomical and far too risky in the minds of regulators and the general public.

3 The US Renaissance: Policy, Time, Cost

Despite the US nuclear industry wasting away via a self-inflicted death of a thousand cuts, NPP development has continued largely unabated through a substantial portion of the rest of the world. France, despite its continual battles with oftentimes militant protestors (Rucht, 1990) has continued to construct new NPPs. Asia in particular has been a hotbed of nuclear activity—Japanese manufacturing giants Hitachi and Toshiba currently factor heavily in the US renaissance. Similarly, the Chinese, who had 9 GW of nuclear capacity by 2007, have an eventual goal of 40GW by 2020. This pace of nuclear construction in China has left some Chinese academics calling for a reconsideration of deployment speed, lest the issues of safety, cost, and energy security occur on an irresponsible development path (Wang 2009).

Results from the construction of new reactors in Japan and South Korea lend some support to industry arguments that improved construction techniques can dramatically speed the path from construction start to commercial operation (Du and Parsons, 2009). However, attempts to construct ABWRs at Longmen in Taiwan have met continual delay and cost overruns, mirroring the less pleasant situation occurring with the first European Pressurized Reactor in OLkiluoto, Finland.

As one might have guessed by the widespread construction and use of new NPPs in Asia, the global nuclear industry never actually went into decline. Nonetheless, the term “nuclear renaissance” has been coined to describe the potential resurgence of the nuclear power industry in the US, and to a certain extent, the UK (Nuttall, 2005), comeback stories which have seemed for over a decade to be unthinkably optimistic. Given this, it is important to understand what has changed to erase, or at least amend, the considerable list of failures which sent US nuclear development into hibernation for two decades.

3.1 **Public Policy to the Rescue**

As was previously discussed, reactor licensing became the leverage point NPP opponents were able to use to delay or cancel construction projects—the key problem being the two stage licensing process. Once construction was completed, utilities were forced to carry their construction loans through the oftentimes long and ugly operating license process (which included RERP acceptance), accruing interest which ultimately bankrupted both PSNH and the Washington Public Power Service. To combat these issues, the NRC altered its licensing procedures in two fundamental ways. The first, pre-construction design certification, allows for the safety certification of a reactor design before construction begins. In theory this allows a utility to take a pre-packed NPP design (>90% of engineering work completed) and begin the new streamlined licensing process.

That streamlined process, the Combined Construction and Operating License (COL), was introduced specifically to remove the “back end” operational licensing application, the hole in the nuclear industries otherwise impressive regulatory armor. The COL process produces a safety finding at the beginning of the construction process, the new reactor only has to pass in-stream and post-construction safety checks the content of which are predetermined at the end of the COL process. This helps insulate the nuclear industry from the worst excesses of regulatory change which afflicted plants post-TMI. However, as of yet, this process is untested and its eventual success or failure will be an important factor underlying the future development of any US NPPs.

Incentive policy is the carrot which has motivated the bulk of new license applications (Joskow, 2006). The Energy Policy Act of 2005 (EPAct 2005) outlines two new policy measures to incent new NPP construction. The first is the production tax credit, at $18 per megawatt hour. The second is a set of loan guarantees initially set at $18 billion and covering up to 80% of a utilities construction costs. The loan guarantee is essential as the financial community remains wary of investment in NPPs following the disastrous history of the 1980s.

3.2 The (Slowly) Changing Landscape of Public Opinion

Other factors aside from regulatory structural changes and direct government incentives have softened the environment for new nuclear. Beginning in the early 1990s, the march of time, combined with an improved safety track record and major political events outside of the purview of the nuclear industry, began to alter the image of nuclear power to the US public. As joint disarmament (SALT talks) redefined the nuclear weapons landscape, and later as the USSR collapsed, the anti nuclear weapons movement lost the most apocalyptic underpinnings of its public support. The linkage between it and the anti-nuclear power movement robbed opponents of NPP construction of the considerable resource and organizational advantages they enjoyed throughout the 1970s and much of the 1980s (Joppke, 1991).

Coupled with this, a lack of dangerous and highly public reactors accidents domestically and internationally has cemented nuclear power as "safer" than at any point in the previous twenty years. After Rosa and Dunlap (1994) observed the crippling impact of TMI on public acceptance of nuclear power, public opinion has move steadily in the opposite direction. Since the early 1990s, public support for generation of electricity from nuclear power has risen from 41% in 1991 to 56% in 2005 (Bolsen and Cook, 2008). Within this general trend, those who live in close proximity to an NPP, or who have personal contact with someone employed at an NPP are significantly more receptive to an expansion of nuclear power in the US than those who do not (Greenberg, 2009). On the other hand, Americans are still, on a national scale, highly "NIMBY" towards the local siting of nuclear power plants. But, the long, successful history of NIMBY movements in the US may not matter for the first wave of new US build. Of the four DOE loan guarantee finalist project locations (Calvert Cliffs in MD, South Texas Project in TX, VC Summer in SC, and Vogtle in GA) *all* are expansions to existing sites. The benefits of this (in addition to existing infrastructure) are that the local population is more likely to accept further construction given the results in Greenberg (2009) and the fact that the emergency evacuation routes from these power stations already exist (preexisting RERP framework), robbing opponents of the intervention tool which factored so heavily in the 1980s worst case scenarios. Additionally, three of the projects, with the exclusion of Calvert Cliffs, are located in states with voting/activist demographics (conservative) that Greenberg (2009) finds are most hospitable to NPP development.

With lessons learned from their past failures, part of this substantial turnaround is attributable to the fact that, this time around, the industry and sympathetic regulators are on the PR offensive, leaving the already weakened anti-nuclear NGOs as the party left playing catch up (Luoma-aho and Vos, 2009) in an overhauled regulatory environment where there is little time to reorganize. In the new licensing scheme, the opportunities for public intervention are now clustered predominantly towards the front, instead of the back end, of the licensing process. If opposition groups cannot quickly organize themselves they will likely miss their best opportunity, as defined by the probability of delay or cancelation, to intervene in the NPP construction process.

3.3 Evolutionary Technological Change and Standardization

Additionally, the industry claims that the reactor designs themselves have undergone marked improvement. The new reactors, so called Generation III+ designs such as Westinghouse's Advanced Passive 1000 (AP1000), General Electric's Economic Simplified

Boiling Water Reactor (ESBWR), Toshiba's Advanced Boiling Water Reactor (ABWR) and Areva's Evolutionary Power Reactor (EPR) are all evolutionary changes from existing reactor designs (which are considered Generations II and III). Theoretically this evolutionary change allows the developers and construction contractors to take their existing knowledge of advanced construction techniques such as open-top and modularized construction and 3D engineering planning and apply them in a natural "evolutionary" way to the new designs (WNA, 2010).

The biggest draw is the potential cost improvement from standardization. The US nuclear industry was hampered by made-to-order designs during their Generation II experiences in the 1970s and 1980s. McCabe (1996) finds that the lack of standardization left substantial cost improvements from construction streamlining unrealized. US NPP developers seem to have heeded this crucial lesson, and of the 28 new reactors under consideration 14 are AP1000s, 4 are EPRs, and 2 are the current Generation III Toshiba Advanced Boiling Water Reactors (ABWRs) which is already in use in Japan, South Korea, and Taiwan (NRC, 2010). Standardization is promising because it has been highly successful in other parts of the world. As Joskow (2006) wryly notes: "[t]he US has at least learned something from the French".

3.4 Environment: Positioning Nuclear Power as a Lesser Evil?

Environmental considerations have not been entirely absent from the debate of new nuclear generation. However, informal discussions with those involved in the construction and finance of the new plants indicate that, financially, concerns over climate change and the (potential) future impact of greenhouse gas restrictions are not explicitly considered in the NPP developers' cost-benefit analysis of new generation.

The issue of climate change is one with mixed implications for nuclear power. On the one hand, nuclear does not score particularly highly on questions of "willingness to pay" (Palmgren et al., 2004) for carbon reductions compared to other more popular technologies (such as wind, solar, and energy efficiency). But, versus its primary baseload competitors, nuclear is slightly less popular than combined cycle gas turbines while being considerably more favorable than coal with carbon capture. On the policy front, nuclear is likely to be treated kindly; in what could be the framework for a climate policy passed by the US Senate, the upcoming Kerry-Graham-Lieberman bill, nuclear power receives its own title in the legislation (Johnson, 2010). Even if this specific piece of legislation is not enacted, the political incentives to support nuclear power may well ensure it receives some form of additional subsidy.

3.5 The Lingering Risks to New Build

Even with considerable changes to both US construction processes and the federal licensing procedure, the feasibility of new nuclear generation is not geographically uniform (indeed, most applications are for sites in the South). Public opposition and brute economics vary greatly across regions and work in concert to shape the ultimate distribution of renaissance construction. The northeast (site of the Shoreham and Seabrook white elephants) remains a somewhat dangerous place for new nuclear development. One recent event speaks to the susceptibility of at least existing generation to local and state reprisal:

Entergy's Vermont Yankee NPP's operating licensing is set to expire in March, 2012. The NRC is currently on track to issue an extension, but the Vermont State Senate disagrees—a

February 2010 vote stripped the plant of its "certificate of public good", without which it cannot legally operate in the state of Vermont. While the specifics of this case only have limited application to new NPP development due to a set of unique circumstances (a voluntary submission to state authority by Entergy in order to purchase Vermont Yankee, dubious legal testimony by Entergy employees, popular vote in an election year), it highlights the potential dangers to NPPs from public opposition. The issues in the case are all related to the perception of safety: the plant suffered a very public cooling tower collapse in 2007 and was found to have been leaking tritium in 2010 (Wald, 2010). This should be particularly concerning to NPP developers because neither issue actually poses a serious safety risk, but their very existence was able to reignite safety concern, and the diffusion of these concerns into the public's view of nuclear power has placed the continued operation of Vermont Yankee in jeopardy. It also suggests that NPP developers should be wary of assuming an automatic extension of their 40 year COLs.

Working out to a broader perspective on safety, despite the substantially improved US safety record US, the risk for a TMI-magnitude accident has not disappeared. Nuclear power plants are what can be considered "normal" systems (Perrow, 1999), systems which, despite our best attempts to curtail risk within them, are still so highly complex that some sort of cascading failure should be considered to inevitably occur. This is the very reason that probabilistic risk analysis is used to evaluate the safety of nuclear power plants. Most of the evolutionary Gen III+ reactors have a substantially lower risk of failure than their older counterparts due to the incorporation of passive safety systems[1] , but it is a failure within the existing fleet which poses a regulatory and public opinion risk to their development. The existential threat is that, as these plants age and/or continue to operate, if one should catastrophically (and very publically) fail it casts the entire development path for new, legitimately safer reactors, into question, and could very well send the US nuclear industry back into the abyss of presumptive infeasibility from which it has recently, and despite industry enthusiasm, only tentatively emerged.

The financial risk of nuclear megaprojects is, in spite of the sunny potential promised by improved construction techniques and design standardization, still substantial. The financial community has remained wary of new nuclear development, dictating the need for the DOE's loan guarantee program. The fear of cost escalation triggered default lingers because there has been no structural change to guarantee that the psychological and organizational factors which created the 1980s white elephant projects cannot reappear. The duty to ensure that infeasible projects are appropriately handled falls to management and shareholders. Rafizadeh and Baker (2009) have discussed the need for transparent management-level "reconsideration triggers" during the development of new NPPs to combat the human nature tendencies which drove the worst of the 1980s nuclear excesses, suggesting that thresholds of cost be set that, once passed, should merit an earnest reconsideration of the project. Still, even with some lessons from past failures inevitably internalized, in the mind of the financial community, the risk of default in the face of uncertain construction time and costs is very real, and is cause for concern.

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[1] Passive safety systems are automated and highly redundant, allowing the control room operators greater time to react. This should hopefully lower the rate of human error which proved to be so critical to the failures at TMI and Chernobyl.

In order to understand the development of "renaissance" nuclear power we must understand how the NPP investment decision is influenced by these lingering risks, and how—or whether—policy might intervene to mitigate them.

4 Modeling the Risk in NPP Investment

4.1 <u>Analytical Framework</u>

In order to analyze the risks associated with new NPP development it was necessary to develop an analytical framework from which risk, policy, and investment value could be appropriately evaluated. Real-Options Analysis (ROA) provided this necessary framework and the accompanying economic logic for risk.

4.1.1 Real Options and Risk

Real-options is an analytical approach which attempts to apply the principles of rational investment modeling, originally developed to price and evaluate investment in financial instruments, to the capital budgeting decisions of tangible projects. Essentially, real investments (such as a nuclear construction project) are evaluated by spanning them with assets which can be traded in an open, complete market using the risks associated with these spanning assets to determine the value of the project. Optionality (decision flexibility) is the key to valuing real projects—in the case of a nuclear power plant that "option" can be as simple as the choice to invest, or it could become as complicated as embedding series of choices to stop, start, or delay construction work within the valuation of the choice to invest.

Real-options valuation rests on the premise of risk neutrality (Dixit and Pindyck, 1994). Either cash flows or the discount rate must be adjusted to reflect the risk embodied by the particular cash flow. The two approaches are mathematically equivalent, and the end result is to say that by adjusting to account for risk, one removes any opportunities for arbitrage between the spanning assets and the project itself. Otherwise, one could buy and sell some combination of the spanning asset and project and profit from the discrepancy--any option value derived from the non-adjusted cash flows is subsequently inaccurate. The risk these adjustments are intended to accommodate are *systemic* risks—risks which an investor could not, under any circumstances, diversify. The rationale for this perspective on risk comes from the Capital Assets Pricing Model (CAPM). Under CAPM, in a complete market, one can diversify away risks which are uncorrelated with the market at large. These idiosyncratic risks should fluctuate purely randomly. And, when placed in an adequately large and diverse portfolio their random fluctuations are drowned out by random non-market fluctuations in the other portfolio assets. For a brief discussion of CAPM and other measures of pricing risk, along with a discussion of the value of market risk, see Damodaran (2010).

4.1.2 Previous Applications of ROA to NPPs

Published real options literature tends to focus on popularly tractable industries such as oil and gas exploration, mining, and information technology, but nuclear power has not been entirely ignored. Multiple authors address differing aspects of revenue uncertainty: Rothwell (2006) tackles the role of revenue risk for a set of hypothetical ABWRs in Texas's ERCOT power market finding the risk premium (5.2% added to the cost of capital) dictated by the operational risks inherent in the ownership of a US BWR. His model takes construction costs as deterministic and investment as instant. Roques et al. (2005) study the option value of British

NPP investment in concert with gas turbine assets under carbon, natural gas, electricity, and carbon price uncertainties. Again, there is no explicit treatment of cost or time to build uncertainty. Similarly, Kiriyama and Suzuki (2004) evaluate the economics of NPPs in a Japanese carbon and electricity market, choosing to focus on how the volatility of a carbon price influences the value of NPP investment.

In the Japanese case, the exclusion of construction uncertainties is highly justifiable given their success with NPP development and standardization. However, because investors are concerned about uncertainties surrounding the first wave of new nuclear ventures in the US from the untested licensing process and yet to be constructed reactor designs, it is necessary to incorporate construction risks in an evaluation of renaissance plants. Roques, Nuttall and Newbery (2006) assess new UK NPP investment using a Monte Carlo simulation approach, taking construction costs and construction duration as normally distributed. In an US context, the DOE's Nuclear Power 2010 Feasibility Study (DOE, 2005) uses real-options to assess investment decisions at licensing and construction toll-gates, allowing the NPP project to be abandoned should uncertainty in cost or expected revenue resolve unfavorably. But, this cost and time-to-build uncertainty is resolved prior to the construction start inherently assuming a fixed-price contract including clauses for loss-recovery in the event of construction delays. In reality, construction uncertainty can only be resolved during the construction process as mistakes are made and schedules are missed (or, as a positive alternative, beaten). Even with the sustained construction successes enjoyed by the French and Japanese, there are a handful of warnings which suggests that cost and time-to-build are very much uncertain (in-stream delays at the Okiluoto EPR and Longmen ABWRs), and that this uncertainty will appear *during* construction.

To find an NPP investment model which attempts to incorporate this "in-stream" uncertainty resolution, it is necessary to return to the analysis which followed in the wake of the US nuclear industries 1980s failures. Assessing the numerous decisions to abandon post-TMI NPP construction projects, Pindyck (1993) introduces the concept that, for projects with high, variable costs and long, uncertain lead times, the uncertainties associated with the project itself—not necessarily its revenues—could most influence the value of the investment. The innovative element of his analysis was the explicit treatment of uncertain time to build and uncertain cost, separating cost uncertainty into elements of technical uncertainty and input cost uncertainty. Schwartz (2004) expands this model to account for uncertain revenue flows and the potential for unexpected loss of project value from external shocks. He applies it to pharmaceutical R&D where projects can face unexpected regulatory intervention from the FDA, or unexpected technical failures while in testing. Additionally, he introduces a framework for extending cost uncertainty to multiple project phases.

While the climate for nuclear power has improved since Pindyck's analysis, the underlying technical dynamics have not changed considerably. Even with the COL, the NPP licensing and construction phase is long—at least 8 years, and during this lead-time both the cost of building the plant and the electricity prices investors rely on to recoup their expenditures are subject to considerable change. Much like the 1980s where NPP investors found the impacts of the 1979 energy crisis short-lived, and the sunny predictions of rapid construction overly optimistic, so too will renaissance developers have to grapple with fluctuating costs and a fluctuating market.

4.2 The NPP Investment Model

4.2.1 A Bird's Eye View

Subsequently, I adopt and modify the model developed in Pindyck (1993) and expanded by Schwartz (2004) to describe the development of a new generation III+ nuclear power plant. The rationale for developing this NPP investment model is to take into account these uncertainties, developing a framework from which to evaluate how specific structural risks (such as construction, regulatory, and electricity price uncertainties) and decision making risks (such as organizational lock-in problems and conflicts of interest among investors) can influence the value of an investment project. Specifically, the goal of this analysis is to assess the loss of value in a nuclear project from:

1. Wariness of US investors of new nuclear build due to the US nuclear industry's legacy of poor outcomes

2. Uncertain input costs which are prone to increase and fluctuate before an NPP developer locks in their commodities and long lead-time components contracts

3. The potential for activist legal or regulatory action which could force a halt to the construction or licensing processes

4. The potential that a reactor may not be relicensed owing to future political, technical, or social realities.

5. Organizational lock-in and mismanagement which keeps projects such as Shoreham and Seabrook from being abandoned when it no longer makes economic sense to continue construction

Understanding these key elements of the investment decision can shed light on the roles of both policy-making and risk-sharing as methods to incent new NPP development. Additionally, these results can give us a clear goal to policy, adding an endpoint, a metric from which to judge claims of learning and construction success, to what could otherwise become an endless subsidization process.

The valuation model operates in three phases. In the first, a series of random NPP development and operations paths are modeled through time via Monte Carlo simulation to capture the breadth of uncertainties. The project first passes through the licensing phase, then the uncertain construction phase, and finally enters operation at some uncertain point in the future. The entire time the project is under development, fluctuating electricity prices introduce an extra element of uncertainty into the decision to continue construction. Next, the expected value of the plant is calculated by starting at the end of operations and moving backwards through time, adding together the discounted realized revenues. For plants in the licensing or construction processes, regression techniques are used to predict the expected value of the NPP from remaining construction expenditures and current electricity prices at each time-step along the development path. If the expected value is negative, a rational investor should halt investment and abandon the project. This application allows the plant to be abandoned while in construction if construction takes an unpleasant track or electricity prices drop to levels lower than was initially expected. The option to delay is ignored because this model is essentially asking the question: “what does it take to get the first new nuclear plants in the US built?”. We are interested in the risks, thresholds, and policies which make the difference between the nuclear renaissance being realized and it being a policy-driven false start for the industry. The third phase of the model travels forward, summing the discounted cash flows of the projects until they are either abandoned (with abandonment timing found in the second phase) or reach the end of their operating license. Appendix 1 contains a more detailed description of the solution algorithm. The remainder of this section describes key mathematical components of the model and the next section introduces the base model parameters, their justifications, and the data from which they were derived.

4.2.2 Conceptualizing Project Cost and Time Uncertainty

The duration of a project is uncertain, as are its costs. In the context of nuclear power, Pindyck (1993) suggests that a linear relationship exists between duration and cost in US Generation II. Assuming this relationship is a reasonable approximation for components of renaissance projects[2], then, for constant rate of construction expenditures, I_K, time to project completion, T_K, and total realized cost, $\overline{K}$:

$$T_K = \frac{\overline{K}}{I_K}$$

Essentially, the more expensive a project becomes, the longer it takes to complete. How the project becomes more (less) expensive depends on the evolution of input cost and technical uncertainties through time as investors learn more about their ability to meet, beat, or exceed construction schedules. In the process of construction, the ultimate realized cost is always unknown until reached, it is the expected cost to completion of a project that changes as uncertainties are realized, and it is this expected cost that must be explicitly modeled. Taking K as the expected cost to completion under uncertainty, the instantaneous change in K, dK, can be described by a stochastic differential equation (SDE). Note that here, and in all other stochastic process which make up the model, dZ_j is the increment to the standard Wiener process for model component, j. The subindexes ic and K denote parameters respectively associated with input cost and technical uncertainties.

$$dK = -I_K dt + \alpha_{ic} K dt + \sigma_{ic} K dZ_{ic} + \gamma_K (IK)^{\frac{1}{2}} dZ_K$$

Intuitively, the first term, construction investment, I_K, reduces the expected cost as the expenditure is made. The second two terms are the components of input cost uncertainty, fluctuating as a geometric Brownian motion—this could also be an arithmetic Brownian motion if the proportional elements were removed. The last term describes the technical uncertainty

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[2] During the 1980s, the input cost induced delays could be directly attributable to redesigns order by the NRC. The analogy to the present day is not so direct: input costs will likely fluctuate during the design authorization process due to the technical feedback from the NRC, but it is likely the input cost uncertainties Pindyck describes will be gone once a design is locked in place and a COL is used. However, given that these plant designs are largely untested and that at least US investors’ assumptions about new build are colored by past experience, keeping this linear relationship should not be particularly problematic.

component of the model—the logic to it is straightforward: projects early in their expected duration (high K) will have larger technical uncertainty than those closer to completion, and, the faster the rate of investment (I_K) the larger the magnitude of the technical uncertainty revealed as more is "done" on the project. The implication is that technical uncertainty cannot be realized without investment—the "true" level of expense cannot be known until the uncertain tasks are underway. γ_K is the technical uncertainty parameter from the variance in cost to completion attributable to engineering and construction unknowns.

4.2.3 The Licensing Phase

In order to model the licensing phase, I assume the expected cost to licensing completion, L, is impacted purely by input cost uncertainties. While input cost uncertainty is typically thought of and is modeled as an expected *cost*, in the case of the nuclear power licensing process it can be better conceptualized as an expected *time* to completion. Because there is a linear relationship between the two, this is not an issue. There is no reason to believe that uncertainty is proportional to remaining expected licensing cost (duration)[3]. Subsequently, remaining licensing costs should follow a purely arithmetic random walk instead of a geometric process. Therefore, for licensing expenditure, I_L, and licensing uncertainty standard deviation, σ_L:

$$dL = -I_L dt + \sigma_L dZ_L$$

Additionally, During the COL application process, expected construction costs are assumed to continue evolving from their initial values while no investment in the actual plant occurs. This means technical uncertainty goes unrealized, reducing the entire construction cost equation to one which mimics a geometric Brownian motion such that:

$$dK = \alpha_{ic} K dt + \sigma_{ic} K dZ_{ic}$$

Here the geometric variation can be considered a combination of commodities and component price increases[4].

4.2.4 The Construction Phase

Nuclear power plants cannot begin construction until an Engineering, Procurement, and Construction contract (EPC) has been negotiated and signed. This long-lead procurement process eliminates the majority of input cost uncertainty by fixing long-term construction commodities prices and ordering long lead-time reactor components well in advance. Because of this I assume that the evolution of expected cost to completion during the construction phase is

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[3] The reality is a bit more complicated. The initial application review phase is likely prone to larger setbacks that are reduced as the process nears completion. But, towards the end of the licensing process, there is a period where the NPP developer must file an Environmental Impact Statement and subject their application to a year of public comment and review—this is the most likely period during which a legal or public challenge of some form would be launched.

[4] Again, this is another simplification. Some reactor designs (such as the ABWR) have already achieved design certification from the NRC. Others (such as the AP1000) are still undergoing design revisions to meet NRC standards. For those which are *not* certified, costs would fluctuate along with the requisite expenditures and design changes during the certification process. This is only an issue for the first wave of new build—once the major designs have been certified, applicants will only face the COL process. For now, however, the design certification process could add another element of uncertainty to certain license applications.

best described by removing the input cost uncertainty parameters so that only technical uncertainties realized during construction can change the expected cost to completion:

$$dK = -Idt + \gamma(IK)^{\frac{1}{2}}dZ_K$$

Note that the transition from the Licensing to Construction phase makes the simplifying assumption that the EPC contract is signed instantaneously upon reception of the COL[5].

4.2.5 Electricity Price Processes

Revenue for NPPs is determined by three primary factors: electricity market clearing price, capacity factor, and O&M costs. Capacity factor and O&M costs are treated as random parameters and are estimated as described in Section 6. Electricity prices are assumed to follow a stochastic process. In the context of this model, electricity price, P_t , is determined by an underlying electricity price, p_t, and any potential carbon price, C_t, such that:

$$P_t = p_t + \omega C_t$$

Where ω is a parameter or process which describes the influence of the carbon price on the overall electricity price.

Leaving carbon aside for the moment, electricity prices exhibit a variety of uncertainties—long term trending risk, temporary price spikes, slightly longer deviations from the long-run mean, and certain deterministic features such as seasonality and on-peak/off-peak price divides (Möst and Keles, 2009). It would seem reasonable to make the assumption that, as a lower cost producer, an NPP will be run whenever physically possible—in this case, the temporary prices spikes and high resolution seasonality components (on/off peak, weekends, etc) are unnecessary to model. Intra-year and long-term uncertainties should be adequate for our purposes. To capture these two elements of uncertainty, I use the two-factor electricity price model developed in Lucia and Schwartz (2002). In this model, the logged electricity price is comprised of three functions, a deterministic element,$f(t)$, shorter-term mean-reverting deviations described by an arithmetic Ornstein-Uhlenbeck process, X_t, and long-term trending risk given an arithmetic Brownian motion, ε_t such that:

$$\ln(p_t) = f(t) + X_t + \varepsilon_t$$

$$f(t) = a + \sum_{m=1}^{12} \beta_m M_{mt}$$

$$dX_t = \kappa_X(X_t)dt + \sigma_X dZ_X$$

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[5] Another major simplification. As an example, Southern Company (Votgle) had signed it's EPC before even entering the licensing phase whereas NINA (South Texas Project) is an equity partnership between NRG and Toshiba. Because Toshiba is the reactor designer, an overall EPC contract is a bit harder to conceptualize. But, allowing input costs to fluctuate during licensing can demonstrate the premium at which an unaffiliated investor (such as NRG) would be willing to negotiate a fixed cost EPC before beginning the licensing phase.

$$d\varepsilon_t = \alpha_\varepsilon dt + \sigma_\varepsilon dZ_\varepsilon$$

Where deterministic component a is a constant and β_m is the seasonal coefficient for month, m and κ_X and σ_X are the mean-reversion parameter and standard deviation, respectively, of the OU process. α_ε and σ_ε are the standard terms for an arithmetic Brownian motion describing the evolution of the long-term value of the electricity price.

A carbon price could take on a number of potential forms, but the simplest would be a constant real carbon tax, C_t. However, if the pricing policy is some variant of a cap-and-trade style market instrument, then C_t is likely to be a stochastic process and could be bounded by ceiling a floor prices, a so called "hard collar".

Clearly in a no-climate policy case, $P_t = p_t$.

4.2.6 Free Cash Flow

This electricity price is then used as the primary input to the free cash flows, FCF, resulting from the operation of the nuclear plant.

$$FCF = (1-\tau)[(P_t - wf)H_t - OM_t(H_t)] + \tau(D_t(\bar{K}) + PTC_t)$$

The remaining terms of the FCF are τ, the deterministic tax rate, wf, the deterministic waste fee, H_t, a random variable of the annual number of hours the reactor is online, OM_t[6], a random variable of operating costs, D_t the depreciation (of the capital costs) tax-shield and PTC_t, the production tax-credit awarded in EPAct 2005.

Given the complexity of the free cash flow formulation and concerns over a lack of appropriate futures prices out to the time horizons necessary to evaluate a nuclear power investment[7], I opt to utilize a discount rate adjustment in lieu of risk-neutral measures for the stochastic processes.

4.2.7 Discounting

4.2.7.1 Risk Premium Assigned by External Financing

Traditionally, a risk premium would not be added to the construction period because the prospective technical risks should be wholly uncorrelated with the market. But, In the case of nuclear power, there have been explicit suggestions that a hypothetical NPP development project will face barriers to financing due to perceived risk, the untested new technology, and fear of potential mismanagement (MIT 2003 and 2009, Tolley et al., 2004). In this case, some external risk premium, presumably a perceived premium based on the project's potential private (idiosyncratic) risk, ρ_N, is present for nuclear projects. This is a considerable departure from standard real options practice where risk premiums are derived from the market price of risk for the spanning securities. But as Tolley et al. (2004) note, a substantial portion of risk in a new nuclear project is idiosyncratic, and in a departure from CAPM orthodoxy, institutional investors are pricing this risk, and it seems appropriate in light of the investor behavior to assign a risk premium external to any which could be derived from the model.

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[6] Why operating costs are a function of reactor capacity factor is discussed in the next section.

[7] 47 years at best from a 3 year application process and highly successful 4 year construction period. The worst cases could approach 60 years if construction or licensing delays push the lead time into decades.

4.2.7.2 Incorporating Risks from Public Opposition

An additional element included in the model is the concept of "catastrophic failure" during the investment phase introduced in Schwartz (2004). This catastrophic failure is the Poisson probability, λ of investment loss, and this probability is ultimately added to the discount rate during the project phases where the investment is susceptible to immitigable loss. In the context of a nuclear plant, and the context of this model, this factor measures the odds that some public opposition can ultimately derail the project ala Shoreham or Seabrook. Schwartz's (2004) incorporation of catastrophic failure (testing failure of FDA intervention) has a direct analogue in NPP development in the form of regulatory or local government intervention such as RERP acceptance, local legislative intervention, or a decisive legal victory for NPP opponents. This is accommodated in the model by discounting at a rate of $r + \lambda$, where λ is the Poisson probability of catastrophic public opposition which cancels the project, leaving it with a value of 0. I assume that the risks posed by public opposition or local government intervention are equally present during the licensing and construction phases.

4.2.7.3 Period by Period Discount Rates

Each individual phase of the project carries with it different risks, and the risk-adjustments for each phase are subsequently different. An investor is exposed to public intervention risk, systematic risk from construction price fluctuations, and their perception of the unique risks from new nuclear development. The construction phase, by virtue of having most input costs fixed by necessity from the long-lead procurement process, does not carry any systemic risk, but it still carries nuclear's perceived risk and the risk of public intervention. The operational phase where free cash flows are received is free from perceptual/idiosyncratic risk and the risk of public intervention. But, the free cash flows are now determined by a unique blend of market driven forces such as electricity prices. In some shape, the free cash flows carry an element of systemic risk. Subsequently:

$$r_L = r + \rho_N + \rho_L + \lambda$$

$$r_K = r + \rho_N + \lambda$$

$$r_{FCF} = r + \rho_{FCF}$$

Where ρ_L and ρ_{FCF} are risk-adjustments to accommodate for systemic risk exposure in each project phase. These adjustment values are derived from CAPM where the risk premium for project phase, j, ρ_j, is determined by the market price of risk and that phase/cash flow's particular correlation with the market (systemic risk), β_j, such that:

$$\rho_j = \beta_j(r_m - r)$$

The more correlated (and subsequently less diversifiable) an investment becomes (higher beta), the riskier it gets.

4.2.8 Option Value

With the constituent elements of the model described, the value of continuing to invest in the plant is the net expected value of the remaining expenditures and resulting free cash flows.

In continuous time, the present value, V_L, from the licensing phase is simply the integral of the discounted licensing expenditures over the duration of the licensing process:

$$V_L = \int_0^{T_L} I_L(t) e^{-r_L t}$$

And similar arguments apply for the construction phase, except we are investing at the rate of I_K. Additionally, as the construction phase cannot begin until the licensing phase is complete, the integral begins at T_L and all construction revenues are discounted at the cumulative rate at the end of the licensing process, $e^{-r_L T_L}$:

$$V_K = e^{-r_L T_L} \int_{T_L}^{T_L+T_K} I_K(t) e^{-r_K(t-T_{COL})} dt$$

Once construction is complete, then the value of the free cash flows is, again, the integral of the discounted cash flows from the end of construction to the end of the licensed operating period:

$$V_{FCF} = e^{-(r_L T_L + r_K T_K)} \int_{T_K+T_L}^{T_K+T_L+T_{COL}} FCF(t) e^{-r_{FCF}(t-T_K-T_L)}\, dt$$

So, ultimately, the value of the project, F, is found by taking the maximum of 0 and the expected value at time 0, E_0, of the net project value, $V_{FCF} - V_K - V_L$. Thus:

$$F = \text{Max}[0, E_0(V_{FCF} - V_K - V_L)]$$

If the expected discounted sum value of the project is positive (discounted revenue flow > discounted licensing/construction outlays) it is rational to keep investing, if the value of the project is negative, the true value of continuation is zero, and the project is cancelled.

Unfortunately, T_K and T_L are uncertain—time to completion is a function of the investment rate and the uncertain cost to completion. When there is a single project stage and revenues are a known constant or fluctuate as a geometric Brownian motion, this uncertainty produces a differential equation with no closed-form solution (see Pindyck, 1993; and Schwartz, 2004).

When the admittedly messy formulation of cash flows is added, even obtaining a differential equation describing the expected value of the project is not feasible. Because there is no closed form solution to the expected value, the valuation problem is solved via a Least Squares Monte Carlo algorithm described in Appendix 1. This numerical solution method was first derived in Longstaff and Schwartz (2001).

5 Data and Model Parameters

5.1 Discounting Parameters

Cash flows in the model are nominal and consequently the risk-free rate must be the nominal risk-free rate. Traditionally, treasury bonds are used to estimate the return to a presumptively risk-free asset (the US government should supposedly have little default risk). This analysis uses a risk-free rate of 4.9%, the average return on the 10-year treasury bond over the past 20 years (ICF, 2010; US Treasury, 2010). And, because this assessment necessarily takes a long view of cash flows, I use the historical (1960-2007) geometric market risk premium, r_m, of 5.51% (Damodaran, 2008a) to determine the systemic risk adjustments associated with different project stages. Inflation is assumed to be 3% as in MIT(2009). This is the average rate of inflation the US has experienced over the last two decades.

5.2 Current and Future Estimated Costs of Construction

In their estimate of the levelized cost of nuclear power, Du and Parsons (2009) find that the cost of new nuclear construction escalated 100%, from \$2000 to \$4000/kW, between 2003 and 2007 as measured both by publically published project costs and the North American Power Plant Capital Cost Index (PCCI) maintained by energy consulting group IHS CERA (MIT 2003, MIT 2009). Since the MIT (2009) cost estimates, the PCCI index, and consequently the presumed cost of new nuclear construction, has declined along with the recent downturn in global economic activity. As of Q3 2009, the PCCI has fallen an inflation adjusted 9%. If we index 2007 to be \$4000 per kW, then the cost of a new NPP as dropped to roughly \$3660 per kW as demand for both construction commodities (steel, concrete, etc) and previously scarce engineering services has waned (IHS CERA 2009). As far as the future evolution of prices is concerned, the crucial question is whether this downward trend will continue or merely be a reprieve from the consistently escalating costs of power plant construction. This project makes the relatively conservative assumption that prices will, in the long-run, continue their steady upward trajectory and not remain completely frozen by structural considerations. Recall the equation describing the evolution of input costs:

$$dK = \alpha_{ic} dt + \sigma_{ic} dZ_{ic}$$

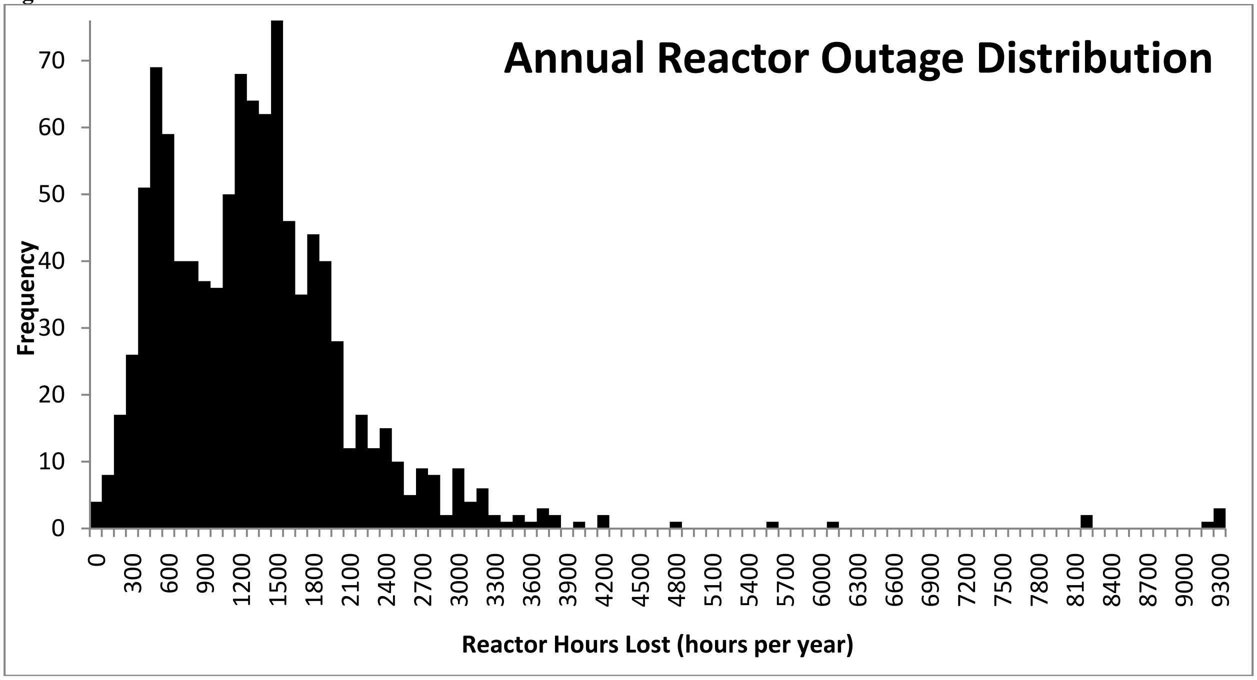
Under the assumption that the past behavior of nuclear capital cost components is indicative of their future trajectory, a regression on the PCCI at six month intervals gives $\alpha_{ic} = .029$ and $\sigma_{ic} = .059$. The extent to which this amalgamation of construction elements is correlated with the market is difficult to determine. In the US, properly trained and staffed engineering services and nuclear-certified manufacturers are limited. However, the international demand for nuclear components is high, and shows no sign of abatement—this trend has even seemed to weather the downturn in the US and global economies. There is no easy way to quantify this structural break in cost volatility. Making a simplifying assumption that only some of the costs are subject to market volatility and the other share are, at least in the short term, frozen by structural factors plaguing the US nuclear industry, I will take the project's $\beta = 0.5$. Plugging this into the CAPM model for the risk premium, $\rho_{ic} = .0275$.

5.3 Plant Capacity Factor

As the US nuclear fleet has aged, learning and consolidation have led to a substantial decrease in the time the average plant spends offline. This increase in the reactor's capacity factor, the amount of time spent online relative to theoretical maximum capacity, is considerable having risen from an average of less than 50% availability in 1970 to less than 80% in 1990, to over 91% in 2008 (NEI, 2009). US reactors regularly provide power in excess of their conventionally rated capacity due to being rated at summer capacity. The temperature differential between the reactor core and the cooling system is lower in summer due to higher ambient temperatures—subsequently, reactors can exceed rated capacity as they operate at higher efficiency owing to the larger temperature gradient during winter months. So, to approximate the capacity factor for an as of yet unconstructed plant I have gathered data on all US NPPs (IAEA, 2009) from 1999-2008 and normalized the reactor hours lost to a capacity factor of 105.5%. 105.5 is equivalent to 9240 reactor hours, the maximum achieved in the dataset.

The mean annual hours lost were 1267. This figure includes exceptional cases such as Davis Besse and DC Cook 1&2 which, for reasons over safety and design were offline all or substantial parts of various years between 1999 and 2003. Capturing these outliers incorporates the small, but potentially non-negligible risk that considerable flaws could make their way past designers and the NRC given the complexity of NPP design and construction. The resulting distribution of hours lost does not fit well to any continuous probability distribution. Subsequently, in order to simulate outage times random draws are taken from the historical data as an empirical probability distribution.

Figure 2 - Estimation of Reactor Hours Lost for US NPPs 1999-2008



The mean value of the historical outages corresponds to 7973 hours online, or a 91% capacity factor. This capacity factor is optimistic compared to MIT (2003, 2009) and Rothwell

(2006), but more pessimistic than various consulting (IHS, 2010) and industry estimates. As a constant distribution, it essentially assumes no learning curve at the beginning of plant operations, but also assumes that, over time, the average Gen III+ plant will operate no better than a hypothetical average member of the current fleet regardless of learning or efficient design improvements. Koomey and Hultman (2007) note that the lifetime capacity factor of the US fleet is 82%, this is a substantial departure from that observation. But, the extended duration of reactor life (40-60 years) and demonstrated learning from the major operators suggests that a lifetime capacity of 91% for new build is realistically attainable.

5.4 O&M Costs

Like capacity factor, continual improvement in US NPP operations had lead to a drastic reduction in the average expense (in dollars per unit production) of producing nuclear electricity. In order to estimate a distribution of O&M costs, data was collected from public utilities required by federal law to report expense information to the Federal Energy Regulatory Commission (FERC) on FERC Form-1 (FERC, 2009). The dataset spans 1999-2008 with the exception of 2000 which was unavailable owing to technical difficulties on the part of FERC at the time of this draft. For the sake of simplicity I aggregate all operational data—including fuel costs—into a single O&M variable.

Because the data is reported as the share of expenses for a particular plant shouldered by a single specific utility, the data suffers issues of partial reporting and inconsistent relative shares reported from year to year. As an example, take an NPP owned by two corporations, Utility A (30%) and Utility B (70%). The data reported in Form-1 only reflects the share of costs from Utility A, which is purely a regulated monopoly. Utility B, who operates in a liberalized electricity market and may sell part of the power from its share wholesale, does not report its share of the costs to FERC. So, in Form-1, the NPP shows up with 30% of its capacity and generation. To account for this issue, where an NPP is owned by multiple utilities, these shares are aggregated into a single entry for a given year. If after this aggregation the reported shares are still less than the total rated capacity of the NPP, capacity, generation, and operating costs for the plant are scaled proportionately to full capacity. This scaling makes the assumption that the reported costs are proportionately representative of the entire plant costs—if cost sharing arrangements between reporting and non-reporting owners are not equivalent based on capacity, the scaled costs will be biased. Additionally, given issues with multiple shares and uncertain accuracy, outlier data for the three-reactor Beaver Valley Generating Station are excluded.

A regression was run on the scaled Form-1 data to generate a reasonable distribution for annual O&M costs for a US NPP, the results of which are presented in Table 1. Initial regression model forms attempted to capture fixed costs (based on capacity) and variable costs (based on energy generated)—results from these models exhibited the strange result that energy generation was negatively signed, suggesting the O&M costs dropped with higher levels of overall generation. While variable operating costs certainly exist in the context of uranium fuel, the primary expenditures for an NPP are associated with constant staffing and extra maintenance outlays during outages. When an NPP is offline, it is typically either being refueled or something is wrong—both of these eventualities require considerable expenditures. Because of the initial results and this intuition, annual reactors hours offline was used in lieu of net generation (in MWh) to determine the impact of availability on operations costs.

Table 1 - Regression Results for US NPP Annual O&M Costs

Independent Variable	Coefficient	Std. Err.	t	P>t
Capacity	85654	5647	15.17	0
Hours Offline	6560	723	9.08	0
Constant	5.64E07	.57E07	9.86	0
R^2=.30	RMSE=3.0E07	N=736	F(2,733) = 154.22	

The residuals from the regressions are fairly normal with the exclusion of outliers from years 2002-2003 of the Davis-Besse Reactor, which underwent $600 million in repairs after the NRC discovered a growing hole in the reactor head caused by a long-running leak of boric acid[8]. Excluding these outliers does not considerably alter the explanatory power of the model.

We can arrange the regression coefficients into an equation for nuclear power plant O&M costs:

$$OM_{it} = \$56{,}400{,}000 + \$85{,}654 * Capacity + \$6{,}560 * Hours\ Lost_{it} + u_{it}$$

Taking hours lost at their average value (1267 hours), a 1260MW plant will spend approximately $172M per year. Putting the NPP's expenditure rate in perspective, divided across average production ($7973\ hours\ available\ \times 1260MW$) this results in a production cost of $17.2/MWh. This figure is reasonable, while slightly above the average production costs for 2008, the plant size of renaissance builds leverage some key economies of scale in NPP operations.

5.5 Electricity Price

Determining NPP economics required choosing an electricity market in which to site our prospective investment. Three liberalized US electricity markets, ISO-New England, PJM, and ERCOT have considerable time-series data and prices high enough (due to natural gas setting the margin price) to justify NPP investment. ISO-NE is attractive economically but carries disproportionate public opposition risk judging by historical precedent (Shoreham, Seabrook) and a series of relicensing skirmishes (Vermont Yankee, Indian Point, Oyster Creek) where the stated concerns (safety, cooling towers) are legitimate, but also likely legal proxies for overall public opposition. ERCOT has a more favorable public environment but the South Texas Project expansion has been well studied by DOE (2005) and Rothwell (2006), even if those studies were prior to 2008's electricity and construction price escalations. This leaves the Mid-Atlantic PJM market which is home to multiple COL applications.

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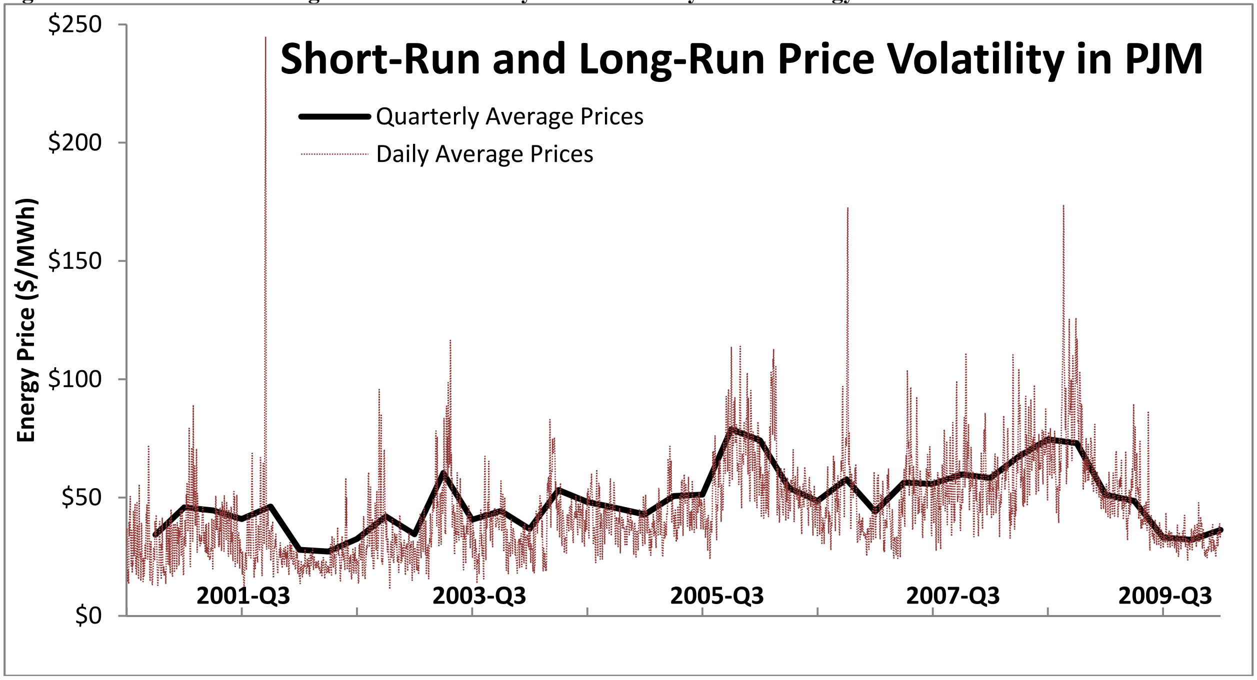
[8] Davis-Besse is, on its own, responsible for the 3rd, 5th, and 10th most likely incidents to have caused a meltdown in US industry history. The 2002-2003 boric acid fiasco is ranked 10th. where are these incidents ranked?

Figure 3 - Short-Run and Long-Run Price Volatility in the PJM Day-Ahead Energy Market



Energy is traded in PJM through long-term contracts, a day-ahead market, and a real-time spot market for balancing energy. Figure 3 demonstrates the daily and quarterly evolution of PJM's day-ahead market from June 2000 to early January 2010. Two constraints help simplify the market picture: nuclear cannot ramp fast-enough to balance and most market participants are hesitant to fix contracts longer than a handful of years—because of these limitations the NPP can be modeled as (successfully[9]) selling all production in the day-ahead market. Note that the model could be used to derive a break-even fixed-cost energy price (eg Rothwell, 2006) the NPP investor would be willing to contract at.

Typically, the risk-neutral parameters for the two-factor model (section 4.2.5) would be estimated from futures or related derivatives prices. However, futures prices would give us an inadequate perception of the electricity price risk as PJM lacks futures contracts of adequate length—upwards of thirty years—and estimating the long-run price changes (ε_t) from these estimates would produce considerably inaccurate results. Instead, I derive the electricity price model parameters in a two-step process. First, the deterministic seasonal components were fit to the historical price data from the day-ahead market. Table 2 gives the parameter estimates. In the deterministic equation, I include a trending term in the hopes of capturing a reasonable estimate for future electricity price drift. Figure 4 demonstrates the model fit and realized electricity prices:

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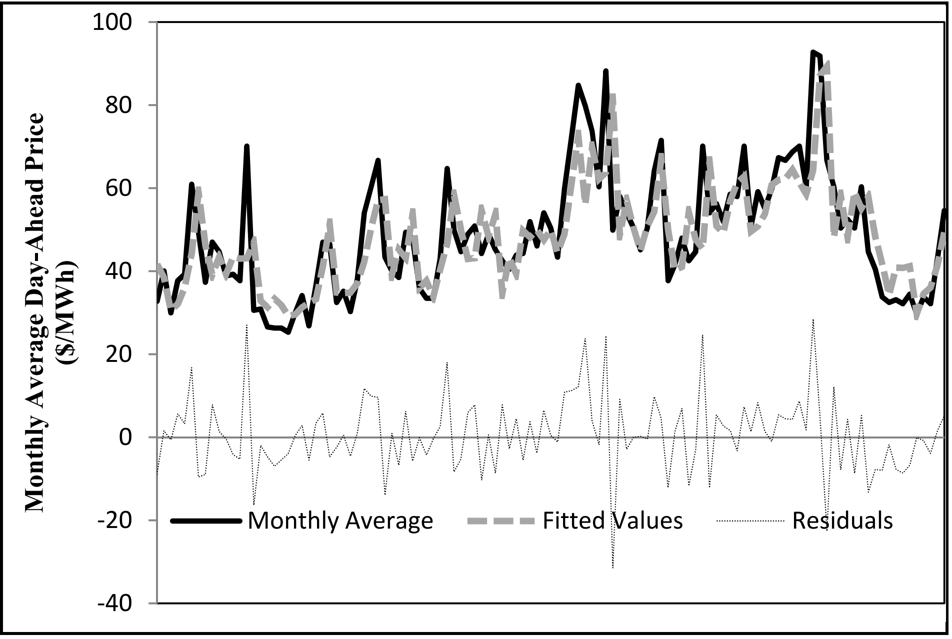
[9] One element of risk that is not considered is that the prospective entry of this new NPP into the day-ahead could drive market prices downward.

Figure 4 - Fitted and Actual Values for Monthly Electricity Price Process

Table 2 - Parameter Estimates for Mean-Reverting Electricity Price Process

Parameter	Estimate
a	3.673
κ	0.254
Trend	3.03E-3
β_{Jan}	0.070
β_{Feb}	0.036
β_{Mar}	0.052
β_{Apr}	-0.008
β_{May}	-0.115
β_{Jun}	0.009
β_{Jul}	0.085
β_{Aug}	0.172
β_{Sep}	-0.141
β_{Oct}	-0.113
β_{Nov}	-0.148



The estimates realistically capture seasonal variation in the PJM market. Prices are highest in high demand months—the cooling loads in June, July, and August, and the heating load in December (the excluded dummy variable), January, February, and March, all of which dictate substantial increases in prices over the remaining five months of more comfortable weather. Additionally, prices seem to mean revert across the space of 4 months ($\kappa \approx .25$) meaning that the non-seasonal price swings from quarter to quarter should be fairly large.

Unfortunately, the resulting drift estimate, while being accurate for the historical data, is ill suited for future projections. At the modeled annual increase in real electricity price of over 3%, the average expected electricity price seen by the NPP in 2060 (at the end of the COL) would be 4.4 times that of today. Even in the presence of some permanent increase in electricity prices (physical resource constraints and increasing global demand), this 4.4 estimate is wildly unrealistic for a commodity which historically exhibits considerable elements of mean reversion. So, to provide a second perspective on future price trends, I assessed future electricity price drift and volatility based on data contained the Annual Energy Outlook 2009 (EIA, 2009) for the Mid-Atlantic region. Using EIA's (2009) historical and projected price changes from the period 2006-2030 yields an estimate of $\alpha_\varepsilon = .061$ and $\sigma_\varepsilon = .029$. Owing to the fact that the AEO-derived data likely underestimates future prices and volatility, and acknowledging that the purely historical data likely overestimates future drift in a long-run mean, I set $\alpha_\varepsilon = .01$ and $\sigma_\varepsilon = .04$. And, again, a careful inspection of model sensitivity to this drift parameter is warranted.

5.6 Carbon Pricing

To gauge the impact of a carbon price on NPP economics, we need some measure of the electricity price sensitivity parameter, ω[11]. Fortunately, this issue has been looked at in some detail by the PJM ISO itself. In a white paper assessing the potential impacts of a carbon price on the wholesale energy market (PJM, 2009), the authors note that:

> Holding all other factors constant, the increase in average wholesale electricity prices in the PJM region corresponds to approximately 75 - 80 percent of the CO_2 price in dollars per short ton. This increase results from the fact that coal units, on average, emit approximately one short ton of CO2 per megawatt-hour (MWh) and coal units determine the price of energy about 70 percent of the time in the PJM Market.

However, the difficulty in modeling a carbon price on the time-scales associated with the development and operation of a nuclear plant is that the long-run changes in generation fleet structure are difficult to predict. For this reason, studies on the price impacts of a market-based climate policy tend to focus on the short-run effects of the carbon price, opting not to comprehensibly model the long-run price changes due to demand elasticities and technological change. However, there is some guidance as to where the inflection points for fuel switching could occur, below these a carbon price is likely to have less influence on the long-term market resource mix. PJM (2009) asserts that widespread switching from coal combustion to natural gas combined cycle turbines does not occur until the real price of carbon reaches \$40 per ton under base gas price assumptions and \$80 per ton under a 50% increase to \$10 per mmbtu. Bolstering this observation, Newcomer et al. (2008) find that the order of dispatch in PJM is little changed even by a \$50 per ton carbon price.

Because of this long-run difficulty, I choose to include in the model a constant carbon price (essentially, a tax) to qualitatively determine the effects of climate policy on NPP attractiveness. When carbon prices are assessed, I first assume $\omega = .775$ (the average of the lower and upper bounds) and second take the price of carbon to be \$15/ton-CO_2.

5.7 NPP Revenue

With electricity prices, O&M costs, and the capacity factor duly handled, we still need values for the remaining elements of the FCF.

$$FCF_t = (1-\tau)[(P_t - wf)H_t - OM_t(H_t)] + \tau(D_t(\bar{K}) + PTC_t)$$

Relying heavily on MIT(2009):, $\tau = .37$, the depreciation schedule is accelerated, and the waste fee (wf) is set to \$1/MWh. To reiterate, the EPAct 2005 production tax credit (PTC) is \$18/MWh.

Because it is not possible to derive the appropriate risk-adjusted drift for each of the electricity factors, the typical method of risk-adjusting the cash flows and discounting at the risk-free rate is not readily applicable. A solution to this is to use a risk-adjusted discount rate. Mathematically, if the risk-adjusted rate is correct, it should deliver the same valuation as using

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[11] For the sake of clarity, while "carbon price" is used colloquially, in terms of units all prices discussed in this analysis are intended to be in dollars per ton of CO_2.

the risk free rate with risk-neutral cash flows. So, In lieu of the ability to directly span electricity price risk with futures, the entire FCF could be ideally spanned by the publically traded stock of a pure-play nuclear merchant generator operating in PJM. Unfortunately, none such corporations exist. The closest analogues in the US market all violate at least one of the three ideal assumptions. But, they can at least offer a first approximation of the risk from the combined impacts of electricity market volatility and operations exposure. Table 3 lists US merchant generators, their exposure to market risk (β), and whether they possess any nuclear assets. The unlevered beta is used as this analysis is, for the sake of simplicity, ignoring debt.

Table 3 - Systemic Risk of US Merchant Generators

Company	**Unlevered β***	**Nuclear Assets?**
NRG	0.86	Yes
Mirant	0.85	No
Dynegy	0.89	No
AES	0.6	No
Calpine	0.6	No
RRI	1.11	No
Average β	.83	

*(LEI, 2009)

NRG on its own is probably the best approximation of the listed merchant generators as it actually operates some nuclear capacity, but NRG still has considerable issues given its cross-market exposure, possession of fossil fuel assets, and some limited regulated operations. As a result, I felt it appropriate to take the average β of the merchant generators as the NPP's free cash flow's exposure to systemic risk. By this measure, at the given level of market risk premium, our hypothetical operating nuclear merchant plant carries a systemic equity premium, ρ_{FCF}, of .83*5.51% = 4.57%.

5.8 Technical Uncertainty

The choice of technical uncertainty is a somewhat difficult given that there is no rich data set from which to reasonably discern the role of engineering and construction difficulties from that of escalating materials prices. Pindyck (1993) is able to separate the *time-invariant* uncertainty from *time-varying* uncertainty by using a TVA panel data set to develop uncertainty estimates for his original application of real-options to the nuclear industry. For an alternative, Espinoza and Luccioni (2005) suggest utilizing the standard deviation of project bids to determine the technical uncertainty—this would certainly seem to be a feasible approach, but we lack the detailed bid information and working across reactor types would overstate the level of uncertainty. As another potential solution, Rothwell (2005) suggests using the standard deviation of the cost estimate to determine construction cost contingency, which we lack. But he also allows for drawing on industry best practices for the estimation of the standard deviation of the cost estimate (which would be applicable to power plant construction). Depending on project stage and the recommender[12], the suggested cost contingency can range from 5 to 50%. We can use these values an input to the equation Pindyck (1993) derives translating the variance of expected cost, σ_{EC}^2 into the technical uncertainty parameter, γ, such that:

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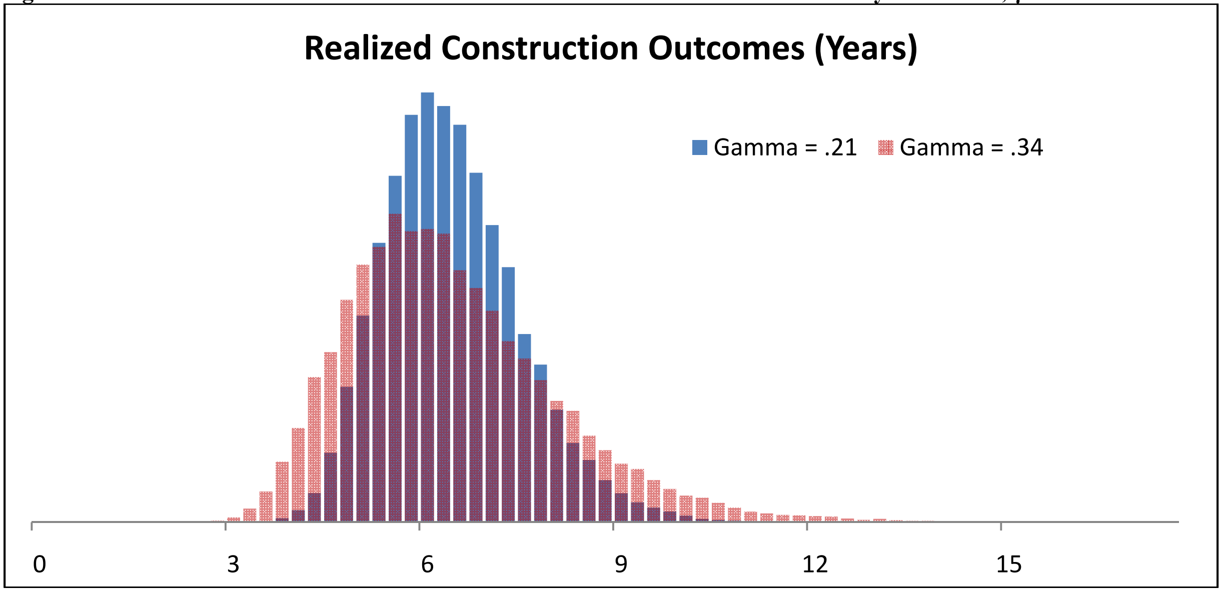
[12] Rothwell (2005) lists estimates by the Electric Power Research Institute (EPRI) and the Association for the Advancement of Cost Engineering International (AACE International).

$$Variance(K) = \frac{\gamma^2 K^2}{2-\gamma^2}$$

Taking σ_{EC}^2 to be the expected variance of cost to completion at the beginning of the project in percentage terms, the equation reduces to: $\sigma_{EC}^2 = \frac{\gamma^2}{2-\gamma^2}$

At a cost contingency of 25%, somewhere between the "feasibility" and "bid" stages of a project from Rothwell (2005), $\gamma \approx .34$. If the contingency is 15%, the amount suggested to be used for a project in the late estimate stages, then $\gamma \approx .21$. Theoretically, the normal distribution of technical uncertainty could end a project in a single quarter, or perpetuate an indefinite construction process. However, in practice, a 30,000 path simulation of construction outcomes with an initial expected time to completion of six years produces a minimum construction time of 3.25 years and a maximum of 12.25. These values line up well with observed outcomes internationally and appropriately bound our exploration of construction uncertainties for nuclear power. Figure 5 demonstrates the range of construction outcomes for the two discussed values of γ.

Figure 5 - Time to Build Distributions for Selected Levels of the Technical Uncertainty Parameter, γ



5.9 Other Parameters

λ is the annual probability of public opposition forcing an NPP in development to stop. Given how the disaster at TMI was the trigger event for both a licensing freeze and paradigm shift in public opinion, a new extremely serious event may cause a similar public outcry against the development of new nuclear. An accident of TMI scale in the current reactor fleet is estimated to occur less than once every 10,000 reactor years (CRS, 2006)—with 100 operating reactors, this is a ≈ 1% annual chance. There are other uncertainties and risks which could derail NPP development as well, particularly a dramatic international incident or a domestic nuclear terror attack. Acknowledging that a domestic accident doesn't *necessarily* freeze development, I assume that the combined probability of all avenues for project loss is 1%, therefore λ=.01.

Also, multiple analysts have concluded that investors will require an extra premium return on new nuclear investments. Tolley et al. (2004) notes that the premium can be thought of as the likely loss in value potentially incurred by taking on a risky new nuclear project. Under a CAPM style valuation, the potential losses from the non-systemically vulnerable construction phase would not merit an additional risk premium as this idiosyncratic risk could be diversified. Regardless, some investors certainly will ascribe a higher risk to nuclear power, and will likely require a higher rate of return. This perceptual/idiosyncratic risk premium on equity, ρ_N, is assumed to be the 3% used in MIT(2009) and Tolley et al. (2004).

5.10 Scenarios

Various scenarios are presented in the valuation results and two merit some further explanation. The first is the exclusion of the perceptual/idiosyncratic risk premium. Because this premium seems to exist for some investors and not others, I have chosen to present the results with and without the premium to capture the impact of differences in investor perception on project value

The second scenario is the policy goal. Ultimately, subsidy policy is an attempt to jump-start the industry and for this to be successful a number of improvements must be realized. First, it must be demonstrated that the design precertification and COL processes do substantially lower NPP lead-time. Second, US NPP construction contractors must demonstrate that they can indeed deliver on their promised construction schedules. There must also be clear indication that design standardization is beginning to reduce costs and lead-times through learning in the construction process. These necessary improvements essentially describe the successes of the Japanese NPP industry. Because of this, our policy goal should resemble the “Japanese Case” of successful construction outcomes and industry-government coordination. Quantitatively, this means that overnight costs are lowered to ~$3000/kW, the reactors only take 4-5 years to build, there is little technical uncertainty, and successful outcomes eliminate the perceptual/idiosyncratic risk premium.

6 Valuation Results and Discussion

Table 4 - Core Parameters for Model Scenarios

Scenario	Parameter	Value
Base Model		
K	Expected cost to construction completion	\$3660/kW
I_K	Construction expenditure rate	\$610/kW/year (6 years to build)
T_{COL}	License duration	40 years
γ_K	Technical construction uncertainty	.21
L	Expected cost to licensing completion	\$23/kW
I_L	Licensing expenditure rate	\$7.67/kW
σ_L	Licensing uncertainty	0*
α_ε	Electricity price drift	1%
σ_ε	Electricity price volatility	4%
α_{ic}	Input costs drift	2.9%
σ_{ic}	Input cost volatility	5.9%
λ_f	Probability of public intervention	1% per year
r	Nominal risk-free rate	4.9% per year
i	Inflation rate	3% per year
m	Market price of risk	5.51%
ρ_{FCF}	Net revenue discounting risk premium	4.6%
ρ_{ic}	Input cost discounting risk premium	2.5%
ρ_N	Perceived/Idiosyncratic risk premium	3%
C_t	Carbon price or stochastic process	\$0/ton-CO_2
No Idiosyncratic Premium		
ρ_N	Perceived/Idiosyncratic risk premium	0%
No Public Intervention		
λ_f	Probability of public intervention	0%
No Input Cost Escalation		
α_{ic}	Input costs drift	0%
σ_{ic}	Input cost volatility	0%
ρ_{ic}	Input cost discounting risk premium	0%
Extended License		
T_{COL}	License duration	60 years
Policy Goal		
K	Expected cost to construction completion	\$3000/kW
I_K	Construction expenditure rate	\$720/kW/year (4 years to build)
γ_K	Technical uncertainty	.1
ρ_N	Perceived/Idiosyncratic risk premium	0%
Climate Policy: Carbon Tax		
C_t	Carbon price or stochastic process	Constant \$15/ton-CO_2

*Assumes government licensing support (cost coverage, delay insurance) is adequate to negate licensing delay costs and discounted value

6.1 Base Economics: Uncertainties and Incentives

Table 5 - Model Results

Scenario	No-Option Value ($/kW)	Abandonment Probability	Project Value with Abandonment ($/kW)
No Idiosyncratic Premium	-$199	70.1%	$33
Production Tax Credit	**$7**	**42.1%**	**$110**
Idiosyncratic Premium	-$377	100%	$0
Premium + PTC	-$223	82.4%	$13
Tax Credit and:			
No Public Intervention	$112	29.5%	$183
No Input Cost Escalation	$110	28.3%	$164
No Intervention or Cost Escalation	$223	17.0%	$253
Guaranteed License Extension	$259	16.0%	$291
Premium + Tax Credit and:			
No Public Intervention	-$160	69.9%	$29
No Input Cost Escalation	-$152	77.1%	$17
No Intervention or Cost Escalation	-$72	60.1%	$49
Guaranteed License Extension	-$39	51.6%	$75
Policy Goal: The "Japanese Case"	$225	17.4%	$256

Currently, under the base set of assumptions, the economics of new NPPs are at best marginal and at worst debilitating. Given the considerable input cost escalation, global recession, and lingering historical concerns over the US nuclear industry, investment in new NPPs without subsidy is decisively unattractive. Just how bad the economics appear seems to depend on investor perception. If they are wary of new nuclear's uncertainties and require a higher rate of return, the plant is an unattractive investment. An investor more comfortable conceptually with nuclear power and the regulatory environment (that is, no idiosyncratic/perceptual risk premium) may be willing to undertake the project. That willingness would be under a production tax credit environment, and would take a true commitment to project abandonment to retain much worth. While, technically, allowing the management team to abandon the project during licensing or construction makes the project a "positive" investment, the value is still largely negligible. Merchant generators and prospective investors will almost assuredly have more rewarding generation investments on tap, making a less than lucrative return on a risky multibillion dollar nuclear project unattractive. This observation is not particularly provocative--the nuclear industry remained dormant for good reason throughout the early 2000s even after the NRCs dramatic regulatory reforms in the late 1990s.

However, if the nuclear industry can deliver to historical best practices for new build—recently this has been the successful ABWR construction in Japan and Korea—then the economics of new nuclear begin to line up a bit better. It bears noting that this analysis is only evaluating the economics of new nuclear vis-à-vis current market prices. New generation will be required at some point in the future, and depending on how steeply the costs of new coal and combined-cycle gas turbine have risen alongside those for nuclear, renaissance could still win out as the best "new" generation if the new designs and improved construction practices live up to their high billing.

To get to this ideal case, however, the nuclear industry (and their investors) must navigate an extremely risky environment to demonstrate the viability of new nuclear power. How risk impacts the willingness to undertake an NPP project is essential to understanding how an investor should pursue development, and how policy can potentially intervene to ensure the construction of the first wave of renaissance build.

6.2 The Impact of Risk

To measure the value of reducing risk, the model was run with certain uncertainties suppressed. The resulting difference in value with and without the risk is what can be conceptualized as a "risk premium" or the value of a renaissance NPP lost because of these key uncertainties. Each case in Table 6 represents a separate combination of suppressed risk parameters—the exact parameters suppressed in each scenario are listed in Table 4. Table 6 presents each risk factor and its attendant value premium.

Table 6 - Quantifying the Risks of Renaissance Build

Risk Factor	**Risk Premium** (Value lost to Uncertainty)
Idiosyncratic/Perceptual	100-200 $/kW
Organizational Lock-In (No Abandonment)	100 $/kW
Regulatory/Legal Intervention	90-110 $/kW
Input Cost Escalation	70-100 $/kW
Relicensing Risk	250 – 350 $/kW

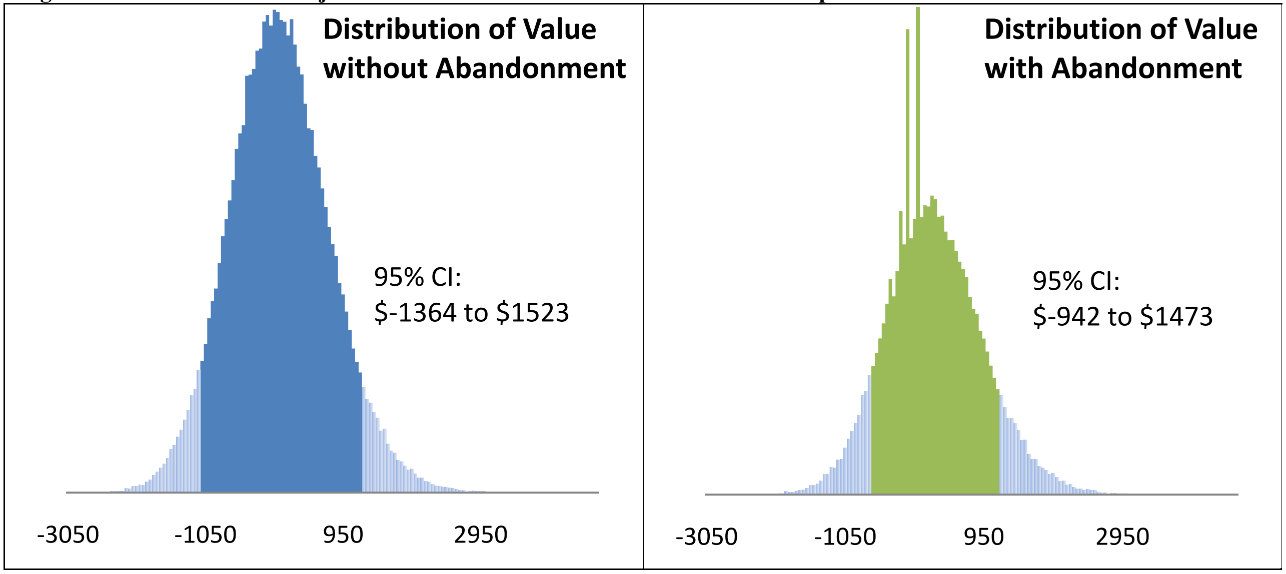
6.2.1 Idiosyncratic/Perceptual Premium: 100-200 $/ kW

The role of perception and belief about the risks from nuclear power has a clear impact on the economics. On a long-lived investment, the discounting of future cash flows that accompanies the designation of risk can be particularly influential. Investors have little desire to tie up a considerable amount of capital in an investment they view as historically too risky that will not deliver a complete payback for 40 years—if they receive any payback at all.

6.2.2 Organizational Lock-In (No Abandonment) Premium: 100 $/ kW

Abandonment (combined with the PTC) is the only mechanism which makes NPP investment profitable at this time. Given the overall marginality of the investment, the ability to head off some of the worst potential outcomes adds $100 per kW in project value. It should, however, be noted that abandonment also reduces some of the upside risk as well. Some projects which initially look poor can, after all, turn out to be profitable in the long-run. Figure 6 shows the distribution of realized project value for the abandonment and no abandonment scenarios of the No Premium + Production tax credit case.

Figure 6 - Distribution of Project Value with and without the Abandonment Option for No Premium + PTC Case



Both figures are scaled identically, but the high abandonment rate (42%) places the bulk of the projects between no value and slightly negative (around - $30 to -50/kW) due to being cancelled extremely early in the development process. The distinct "spikes" in the abandonment histogram are the result of simulation paths canceled at the same development time step—because the investment rate is constant, all canceled projects at a specific time have experienced the same cash flow outlays. Most plants are cancelled at the end of the licensing phase if construction costs rise too high or during the first quarter or through construction if significant technical setbacks are encountered.

While Abandonment can add a fair amount of expected value to the project, another area where it improves investment dynamics is in the risk profile of the NPP investment. The Value at Risk (VaR) from the plant is the largest loss that can be expected with a given confidence level. In this context, at a 99% confidence level, we would find the 99% percentile largest loss of value in the simulation. Because the model produced a Monte Carlo output, the simulation paths only had to be separated into percentiles to find VaR. Table 7 lists the downside risk at three different levels of confidence.

Table 7 - Project Value at Risk (VaR) with and without the Abandonment Option for No Premium + PTC Case

Confidence Level	**99%**	**95%**	**90%**
Value at Risk without the Abandonment Option	$1630 per kW	$1160 per kW	$905 per kW
Value at Risk with the Abandonment Option	$1205 per kW	$712 per kW	$441 per kW
Reduction in Value at Risk from Abandonment Option	$425 per kW	$458 per kW	$464 per kW

We can see that abandonment reduces the project VaR by over $400 per kW at all confidence levels. Essentially, while improving overall project value by $100 per kW, abandonment reduces the downside risk by well over $400 per kW. If downside risk forms any of the wariness which motivates the perceptual premium then a firm commitment to project cancelation in the face of harsh economic realities should reduce that premium.

However, over-optimism and principal-agent conflicts (between management team and investors) could lead an organization to be "locked in" to its construction path. If investors believe this could be the case (and historically, it has occurred) then an unwillingness to abandon adds $100/kW of risk to the project, and exposes investors to much greater downside risk than would otherwise be possible under "rational" management. In this sense, the legacy of poorly managed projects from the 1980s may still haunt renaissance build.

6.2.3 Regulatory/Legal Intervention Premium: 90-110 $/kW

An investor's view of the potential for regulatory failure or legal intervention in the US can make the difference between the project being a clear "no" to once which at least merits further investigation. Eliminating λ reduces the level at which the project's cash flows are discounted, and subsequently raises project value. However, as long as the current fleet remains in operation and there is no safe resolution to the waste issue, there will be a linger risk that some accident will tarnish the reputation of the industry, and this concern produces a 90-100 $/kW loss in project value.

6.2.4 Input Cost Escalation Premium: 70-100 $/kW

Volatile costs and a general upward drift are bound to be of great concern to investors. To accommodate this risk, investors should be willing to pay, at a premium, an addition $70-$100/kW to lock in the prices of commodities and long-lead components before even entering the relatively uncertain licensing process. While this loss of value is the lowest of the studied risks, it is still considerable, and should factor heavily into the investment decision.

6.2.5 Relicensing Risk Premium: 250-350 $/kW

Generation III+ NPPs are designed to run for at least sixty years. However the COL process only allows for an initial license of forty years, relegating the remaining twenty years of functional life to face a relicensing process. While an increasing portion of the current fleet of US NPPs have obtained twenty year extensions there are two potential barriers which make it inappropriate to assume a license extension is a foregone conclusion for renaissance build. First, certain plants are running into *ex post* relicensing intervention due to outdated design concerns at the state level. Both Indian Point and Oyster Creek lack cooling towers (perfectly acceptable at the time of their construction), and local interveners have leveraged this absence to place their continued operation into question. There is a substantial possibility that safety or environmental regulation enacted during the operational lifetime of current renaissance build could raise the compliance costs of relicensing to a point where the effort is no economical. Second, the political climate for nuclear can undergo a great deal of change in fifty years (10 years of construction/licensing + 40 years of operation). A severe domestic accident or terrorist attack could bias public opinion against relicensing measures. Perhaps more saliently, public opinion towards continued nuclear operation may, in the long-run, be tied to the successful resolution of the "waste problem". Many states, such as California, already have nuclear bans which remain in effect until the US constructs a permanent nuclear waste repository. Current disputes over the Yucca Mountain geological repository have relegated what was once considered the "solution" to the policy backburner. Ultimately, there is no safe assumption about the likelihood of obtaining a license extension—the relicensing risks render the valuation lifetime (40 year COL) shorter than the designed lifetime (60+ years). Significant investment value to is left unrealized due to uncertainty and risk.

7 The Role of Policy

Clearly, the economics of new nuclear are still marginal. We can see the ultimate benefit from learning and reductions of uncertainty from the Policy Goal model run. However, how renaissance nuclear gets to this goal depends on the willingness of investors to actually undertake the critical initial wave of NPP projects. In this section I assess the direct options for further subsidy of NPPs at federal and sub-federal levels. Also included is an exploration of climate policy on the economics of new NPPs, the results of which suggest that the only federal level policy that will matter is one which tackles the climate change problem.

7.1 Federal Opportunities for Direct Subsidy and Risk-Reduction

The present size of the loan guarantee program is designed to ensure the construction of up to 10-12 new reactors. But, only the first 6GW of new nuclear capacity fall under the production tax credit while the model results suggest that the PTC is a crucial component of reactor economics. If this 10-12 goal is to be met, and the US licensing is to be properly tested, further subsidy is necessary. One crude but direct method would be to extend the PTC to all loan-guarantee recipients and possibly raise the value of the credit should the current subsidy prove to be inadequate..

However, given some of the unique uncertainties facing nuclear power, more effective, and potentially more equitable (from a societal perspective) policy measures are available to incent a first wave of new construction. The single largest risk-induced premium on the NPP investment is the COL duration at 250-350 $/kW. If a certain portion of new build was to be automatically afforded a 20 year license extension (or equivalently the lost value from license non-extension should politics intervene), the other inherent risks are not removed but the potential reward is much greater. This is adequate to incent investment without perceptual risk, and nearly enough so even with an added wariness towards new nuclear.

Another alternative would be to directly address the potential lost value from public intervention. EPAct 2005 included provisions for loss-recovery from 1-2 years of licensing delay, but this has already been assumed in the model runs. A more robust insurance policy against public intervention and construction/licensing delays could also add some measure of value, potentially up to $110/kW.

As the goal is to see these plants constructed to actually test the licensing procedure and domestic construction capabilities, indemnifying the loss of value that occurs from discarding the abandonment option may be a policy option—this adds 100 $/kW in project value.

7.2 Sub-Federal Risk-Sharing and Incentive Measures

That is not to say that federal level policy is the appropriate avenue to incent NPPs. There are a number of parties (internal and external to the investment) which stand to reap the benefits of new NPPs. Some of these risks fall to the industry itself to resolve. In the case of the abandonment premium, “lock-in” isn’t necessarily an irrational decision if the reactor designer is a member of the NPP ownership group. In industry consortia, such as the equity partnership between NRG and Toshiba to construct the STP ABWRs, there are likely conflicting interests over the role of abandonment. Toshiba has substantial incentive to continue construction if the construction outcome looks promising even though on a single project basis low electricity prices are as much a reason to abandon as unexpectedly high construction costs. But the reactor designer has the potential for substantial profits should construction turn out well, motivating other merchant generators or utilities to standardize on its design. In this case, it may make more sense for the designer to cover this risk contractually with the remaining investment partners instead of relying on government to provide an even higher level of subsidization.

In standard regulated rate of return markets, risk is shared between the monopoly utility and the rate payers (and the federal government if incentive policy is involved). Rate of return regulation inherently increases the value of an NPP because the capital expenditures (in this case the NPP itself) are ultimately bundled into the rate base. An additional incentive available to regulated utilities is the ability to raise rates to finance construction or Construction Work in Progress (CWIP) financing. CWIP is typically highly contentious, but appears to be a necessary subsidy for a new utility NPP without a loan guarantee and with little hope of having access to the PTC. This can be seen in the decisions of AmerenUE and Florida Power & Light (FPL) to abandon their construction plans for a new EPR and new set of ABWRs, respectively. Each was denied CWIP. In the case of AmerenUE, they failed to overturn a long-standing Missouri state law barring the provision of CWIP for new nuclear build (WNN, 2010). For FPL, the Florida Public Utilities Commission denied their request for a CWIP rate increase (FPL, 2010). These abandonments stand in stark contrast to the planned Vogtle AP1000s, where primary investors, such as Georgia Power, have been allowed CWIP by their regulators (WNN, 2010).

Meanwhile, the model results seem to support the general conclusion that the electricity price signals in a liberalized electricity market are not adequate to incent the construction of substantial base load power (similar to results in DOE, 2005 and Rothwell, 2006). However, one typically overlooked aspect of NPP economics (of which this analysis is also guilty) is the potential for merchant nuclear to extract significant value from the provision of capacity payments.

PJM established a capacity market in 2007 to send long-term price signals to IPPs, demand-aggregating entities (for demand response and energy efficient capacity), and transmission investors. The Reliability Pricing Model (RPM) has thus far had great success. While prices have been volatile from year to year (there are annual auctions on the capacity needed three years in the future) jumping from $16/MW-day to $200/MW-day depending on year and location, the current level of prices in some locations could be promising for new nuclear. As a "back of the envelope" reference, with a credit of $100/MW-day[13], an NPP which is constructed on schedule (three year licensing, six year construction) gains added value of $320/kW in the no premium discounting case and $220 in the premium discounting case. Those values are enough to substantially change the economics of an NPP (although the premium case is still negative NPV). As the risk of base load construction is now shared between the investor, the government (tax credits/loan guarantees) and the electricity consumers of PJM (via charges levied on their Load Serving Entities (LSEs) which pay for the capacity credits), the economics of new nuclear improve considerably. However, the capacity market is only bid out to three years, and the lead-time on an NPP introduces the substantial risk that transmission congestion will be alleviated or new generation (or energy efficiency and demand response) will be added,

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[13] $ 100MW-day = $0.1/kW-day = $36.5/kW-year

eliminating the need, and subsequently the incentives for new capacity. For this reason new nuclear would need a firmer projection of capacity credits than is currently feasible.

Other additional sub-federal measures exist, such as Ohio's addition of generation III nuclear to its "Alternative Energy Resource Standard" (DSIRE, 2010) which could make nuclear more attractive by virtue of being an option to meet Ohio's alternative energy mandate.

7.3 Climate Policy as Nuclear Energy Policy

These risks are substantial and can alter NPP economics to the tune of hundreds of millions of dollars. Up to this point, the risks, be they from construction delay or public intervention, have asymmetrically skewed towards the negative. But, conversely, a climate policy, while not necessarily intended to incent the construction of new NPPs, has the potential to introduce asymmetrically positive risk as any increase in carbon price is likely to raise electricity prices. Table 8 shows the extent to which a CO_2 price of $15 per ton can improve the value of an NPP.

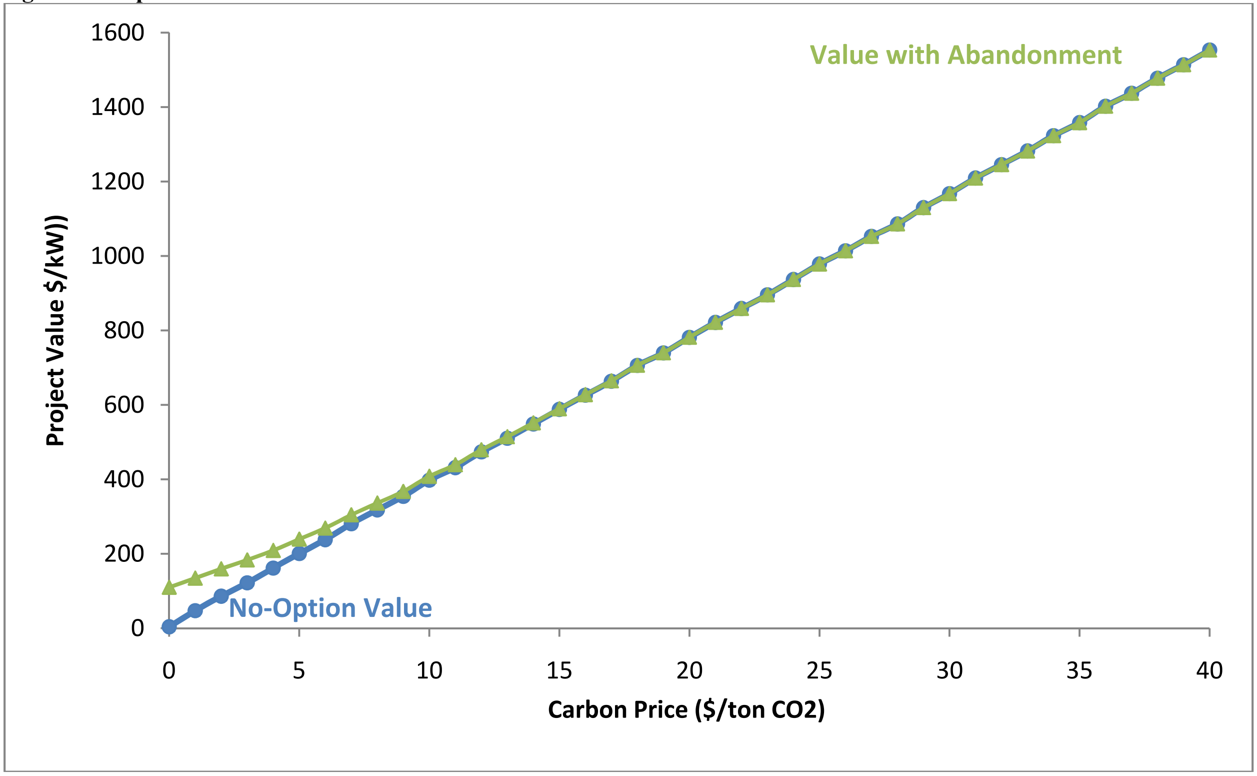
Table 8 - NPP Value under a $15/ton CO2 price

Scenario	No-Option Value ($/kW)	Abandonment Probability	Project Value with Abandonment ($/kW)
No Idiosyncratic Premium	$387	5.8%	$398
Production Tax Credit	**$585**	**1.4%**	**$587**
Idiosyncratic Premium	$63	35.7%	$127
Premium + PTC	**$212**	**17.4%**	**$236**
Policy Goal: The "Japanese Case"	$835	0.1%	$835

What is striking here is that this increase in value comes at a carbon price that falls far short of most serious proposals in congress. As an example, the Cantwell-Collins CLEAR Act (Office of Senator Cantwell, 2009), a bipartisan cap-and-dividend proposal with a hard price collar, sets its price floor to grow at 6.5% real annually. Starting a $7/ton, if the carbon price remains at the allowance price floor, the $15/ton price given in this example will be exceeded by 2024, only five years into the operation of a construction riskless (3 year licensing, 6 year construction) NPP project.

To estimate the climate policy-induced gains in value an NPP prospectively receives, the No Premium + PTC case was modeled through a range of carbon prices from $0 (BAU) to $40 (the low gas price CCGT switching threshold in PJM, 2009). While this method (a constant carbon tax and constant electricity price sensitivity) is not a likely reflection of reality, it qualitatively demonstrates the extent to which climate policy can incent the construction of nuclear power. Figure 7 presents the results.

Figure 7 - Impact of a Carbon Tax on NPP Economics



The indication is that any meaningful (or not so meaningful) climate regulations will make renaissance nuclear a more attractive merchant investment. It only takes a price of $5/ton-CO₂ to reach the equivalent value of nuclear's no-carbon price policy goal. With a substantial enough climate-policy, direct policy intervention in the nuclear investment process is largely unnecessary at a federal or sub-federal level. In some senses, successful climate policy would render the risks of NPPs moot relative to the potential gains in project value from the higher revenue stream.

There are signs, however, that a climate policy would offer another avenue for direct federal subsidization. Some proposals have called for the direct allocation of emissions allowances to new nuclear—the net effect of this would be that the NPP receives a direct subsidy from their (presumably resold) allowances, and indirect subsidy from the electricity price effects of a climate policy. In this case there would be little financial chance that an initial wave of renaissance NPPs is not constructed.

8 Sensitivity of NPP Project Value

Understanding that climate policy can highly influence an NPP investment decision, or, more accurately, the current *beliefs* about the likelihood of a carbon policy can influence an NPP investment decision (as we have no present climate policy), it is worth asking the extent to which other differences in belief about the parameters influencing nuclear power have on investment value. Of particular interest are the Market Price of Risk, the "beta" of an operating merchant nuclear power plant, and the future track of electricity prices.

8.1 Model Sensitivities

Figures 8 – through 10 visually depict the sensitivity of the model to changes these most uncertain parameters. These comparative statics can demonstrate the influence a parameter misspecification could have on the overall model results. All of the sensitivity runs are under the No Premium + Production Tax Credit assumptions.

Figure 8 - Sensitivity of NPP Value to the Market Price of Risk

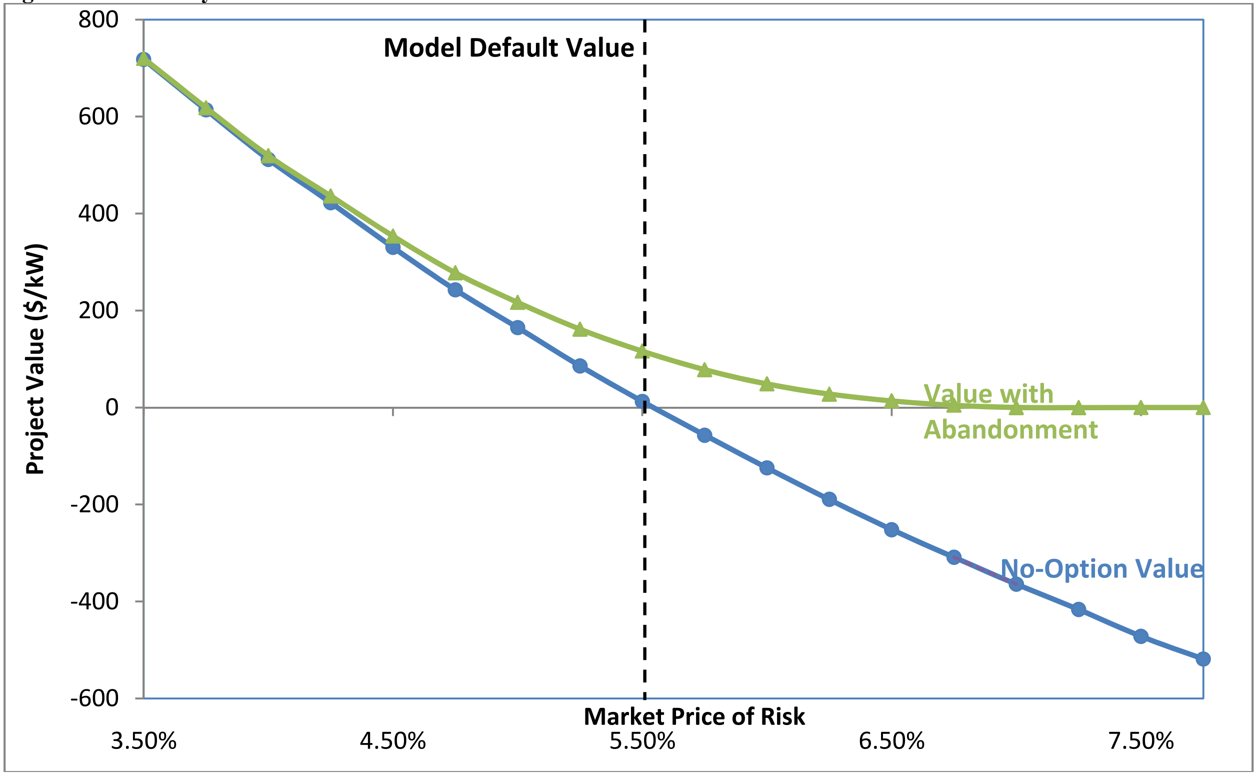


Figure 9 - Sensitivity of NPP Value to Systemic Risk Coefficient, Beta

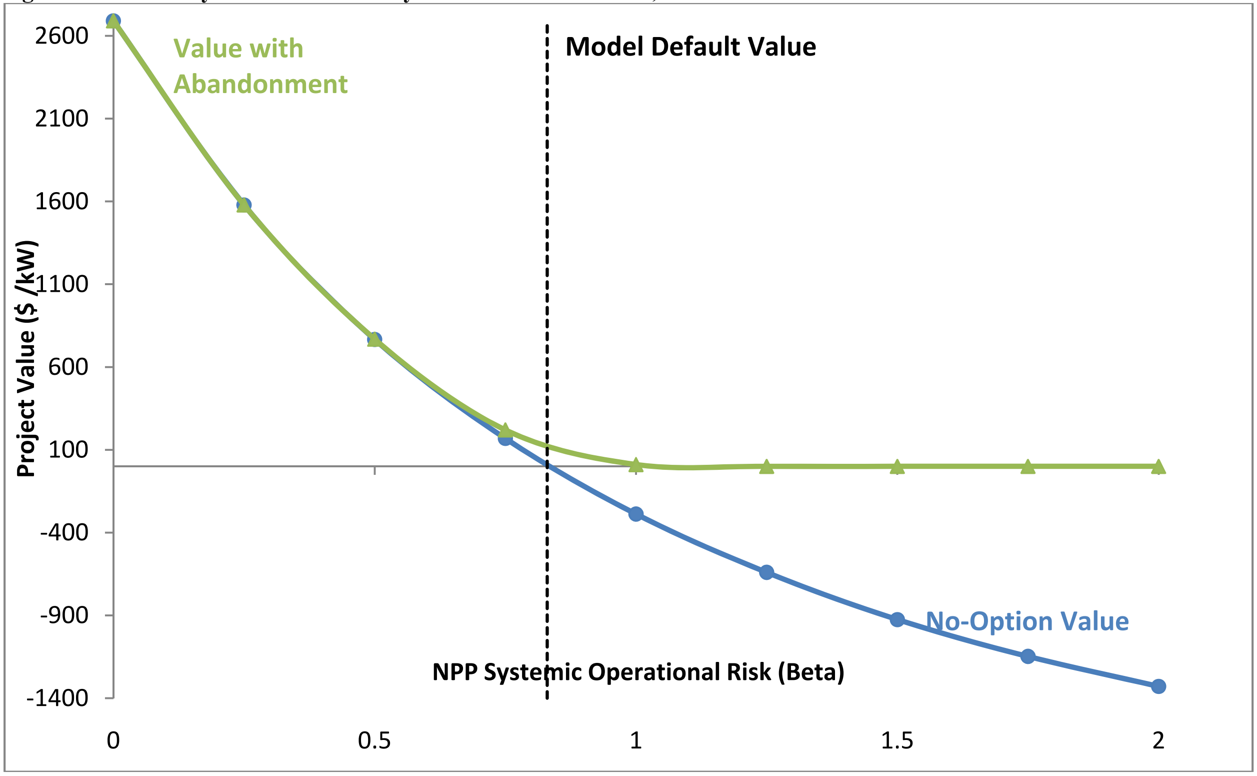
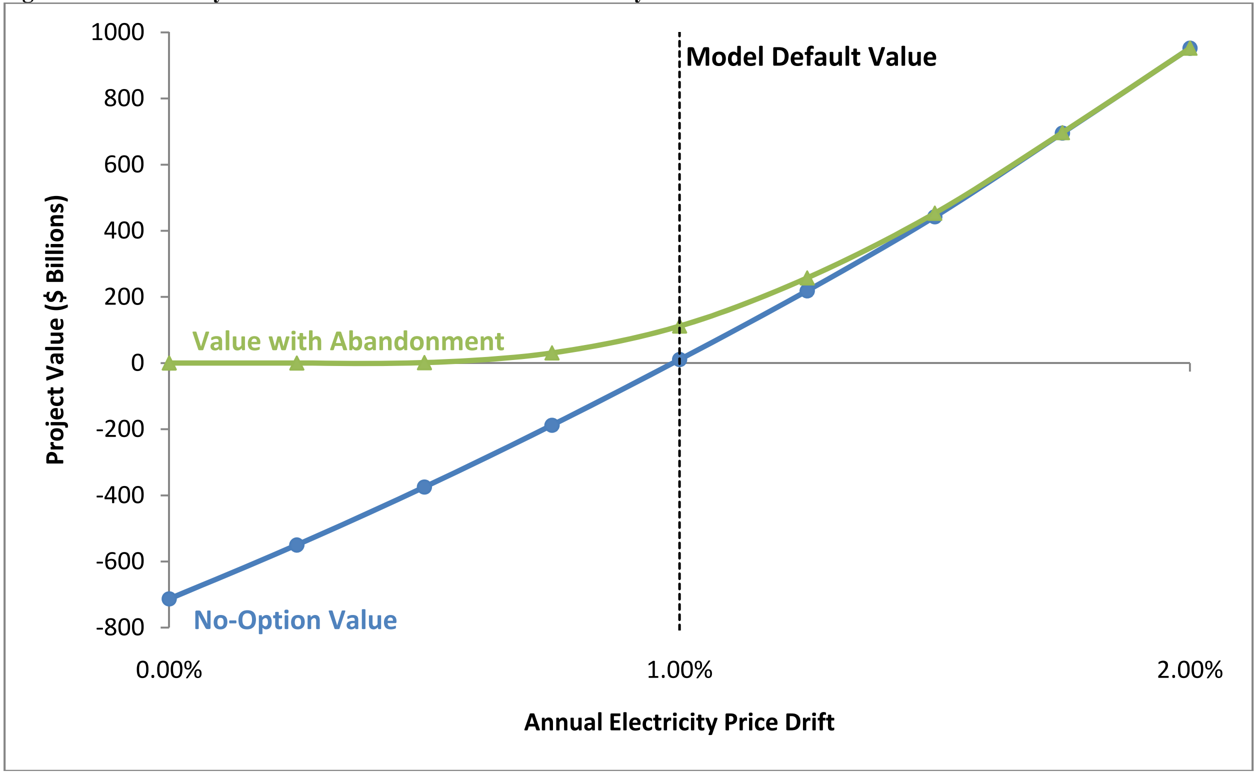


Figure 10 - Sensitivity of NPP Value to Drift in PJM Electricity Prices



There is no well-agreed upon price of risk in the financial community. Damodaran (2010) surveys the state of the "equity risk premium", which can vary by as much as 4% depending on the specification from a low of 3.36% for an "implied" geometric premium on treasury bonds to 7.4% using the arithmetic average differences between stock and short-term bonds from 1900-2005. This analysis attempted to play the middle ground in selecting geometric average difference between stocks and short-term bonds, but a number of other specifications would have been equally justifiable, and each would play a significant role in determining NPP desirability by producing swings in value of up to $800/kW (see figure 8).

Similarly, as nuclear is extremely sensitive to the discounting parameters, the operational beta—the degree of systemic risk from operating in a restructured electricity market—has a profound impact on NPP investment value. Figure 9 displays the sensitivity of project value to the equity beta, and this sensitivity is enormous. Recall Table 3 which compared the unlevered betas of us merchant generators. The range there spanned .6 to 1.1, that same range produces a swing in value from +$600/kW to -$400/kW.

And, if the electricity price drift was incorrectly specified even slight changes in the parameters can alter project value considerably. Beliefs about the future track of the economy and the future resource mix of the PJM region could have substantial impact on the perceived value of a new NPP.

Overall these three parameters are highly influential because of the long time-scales involved in the construction and operation of an NPP. Even a slight perturbation in the exponential growth of electricity prices or the discounting of future cash flows can dramatically alter the value of an NPP in the eyes of an investor.

8.2 Uncertainty and Investor Belief

The theory employed to value the NPP and potential policy incentives is that in the presence of appropriately accurate market data and sets of assumptions, ROA should provide the exact, arbitrage-free value of an NPP. However, given the sensitivity of this investment model to relatively minor perturbations in the base values, any misspecification, and, this is assuming there even *is* any true specification, of the model parameters results in relatively large swings in project value. Some of these values, particularly the market price of risk (a source of academic and practitioner debate) and arguably the drift in electricity prices are areas for legitimate disagreement amongst investors. The time scales one needs to evaluate an NPP seem to be uniquely uncooperative in providing accurate parameter estimates. When coupled with the perception risk premium (or the lack thereof), the role of belief and assumption in the valuation of an NPP is quite clear. Some investors will find that the uncertainties of new nuclear, and their reasonable beliefs about certain classes of parameters, make an NPP project appear drastically unfavorable. Others may see a case of likely and substantial profit.

Roques et al. (2006) astutely notes this lack of uniformity, at least across markets, such that "countries where perceived risks in nuclear power are lower might have a much smaller gap in the weighted cost of capital between [nuclear and non-nuclear] options". Conversations with financial professionals have given a similar picture of the prospective nuclear investor landscape. Some investors are highly comfortable, by virtue of disposition or prior experience, with nuclear power but with a substantially more wary group forming the basis for Tolley et al.'s (2004) observation that [a risk premium of] 3% is a realistic **lower bound** [emphasis added]". We may already be seeing a realization of divergent perceptions over the economics and uncertainty outlook of renaissance build. Two current NPP cases in particular suggest that a variety of investors, who are, for all intents and purposes, seeing the same information as one another, are interpreting this information in drastically different ways.

In Texas, Nuclear Innovation North America (NINA), the NPP development partnership between NRG and Toshiba has recently settled a $32 billion lawsuit with San Antonio's CPS energy, allowing them to reduce their exposure to the proposed South Texas Project ABWRs. In CPS's stead, there are continuing rumors that Tokyo Electric Power Company (TEPCO) is seeking to purchase a stake in the project. Similarly, in order to pursue the expansion of its Calvert Cliff's plant, Constellation Energy partnered with Électricité de France (EDF) to form Unistar Nuclear Energy. After initially forming the development partnership, EDF purchased a minority stake (49.99%) in Constellation. The US NPP market is open to investors from around the globe and the hesitance which characterizes US investors need not apply to those with different assumptions entirely about the prospects for new build. As Japan and France are the two historical success stories in the nuclear industry, EDF and TEPCO have had considerable positive experience with Areva and Toshiba in their common home countries. TEPCO in particular has seen Toshiba's considerable success with the ABWR in Japan and neighboring South Korea. These companies are primed by their existing relationships and comfort level with their NPP partners to be more open to a nuclear investment.

9 Conclusion

The risky history of the US nuclear industry was introduced, discussed, analyzed and the resulting analysis was used as to inform the development of a ROA model to determine the investment risk of new NPPs. The results quantified risk, and found that these risks are substantial, rendering the current economics of new NPPs in the PJM market questionable. However, there are substantial gains to be had from new build if industry predictions about future cost levels are accurate. Numerous incentive policies at a federal level and targeted risk-sharing measures at the market level can turn the economics of new nuclear favorable, and ensure that the first wave of new build is actually constructed. And, once investor heterogeneity and the potential for market-based climate policy are taken into account, it appears as though new nuclear may be a viable investment at current rates of subsidy.

Given all of this, the United States, whether wittingly or unwittingly, has implicitly entered into a risk sharing agreement with the other major economies to field test the promising but uncertain benefits of new nuclear. The $54 billion in loan guarantees and $6 billion earmarked for tax credits will serve to incent the construction of 10-12 renaissance reactors. While the United States constructs its own fleet of new reactors, new build in Europe, China, and India will form a growing body of evidence of the ability of NPP developers and construction contractors to successfully, and economically, complete the construction of renaissance nuclear technologies.

While this new build should produce a clearer picture of the risks of new NPPS, what matters in a US context is the ability of the first slate of new build to demonstrate that the improvements regulatory reform has promised actually do materialize. US build will inform the global nuclear picture, but it will also answer crucial questions about the ability of the NRC to turn around license applications in a reasonably timely manner, and the ability of US construction contractors to consistently meet costs and deadlines. Even if costs and construction times don't begin an immediate decline, a slight indication of those occurrences and clear, non catastrophic construction outcomes should calm the fears of US investors. With the proper incentives in place, the burden falls to the industry and regulators to demonstrate that generation III nuclear power is, or is not, a viable energy resource for the United States in the 21st century.

Appendix 1: Glossary of Model Terms

Reference for Various Model Parameters

dZ_j	Increment to the standard Wiener process for model element, j
t	Time, t
Construction	
$\bar{K}$	Realized cost to completion
$\bar{T}_K$	Realized time to completion
K	Contingent expected cost to construction completion
I_K	Construction expenditure rate
α_{ic}	drift of input cost GBM
σ_{ic}	Standard deviation of input cost GBM
γ_K	Construction technical uncertainty parameter
Licensing	
L	Contingent expected cost to licensing completion
σ_L	Licensing input cost uncertainty parameter
I_L	Licensing expenditure rate
Electricity	
P_t	Total electricity price
p_t	Base electricity price
X_t	Electricity price mean reverting, short-term uncertainty component
κ_X	Mean-reversion parameter
σ_{ic}	Standard deviation of mean-reverting shocks
ε_t	Electricity price geometric long term uncertainty GBM
α_ε	Drift of electricity price GBM
σ_ε	Electricity price GBM standard deviation
$f(t)$	Electricity price deterministic component
a	Base parameter of deterministic electricity price component
$\boldsymbol{\beta}$	Vector of deterministic monthly components of log electricity price
ω	Electricity price carbon price sensitivity parameter
C_t	Carbon tax rate
Cash Flows	
FCF	Free cash flow
OM	Random variable of O&M costs
H	Annual reactor hours online
PTC	Production Tax Credit
wf	Waste fee
τ	Tax rate
D	NPP depreciation tax shield
Discounting	
λ_f	Poisson probability of catastrophic public opposition or regulatory intervention
r	Real risk-free rate of capital
r_m	Expected return of the market
m	Market Risk Premium
ρ_N	External risk-premium owing to historical/perceived idiosyncratic concerns
ρ_L	Systematic risk premium for licensing
ρ_{FCF}	Systematic risk premium for free cash flows
r_L	Risk-adjusted discount rate for Licensing
r_K	Risk-adjusted discount rate for Construction
r_K	Risk-adjusted discount rate for free cash flows

Appendix 2: Solution Algorithm

Following Schwartz (2004) I have included a step-by-step description of the Monte Carlo-Least Squares solution process. Note that n indicates a Monte Carlo path, t a timestep, and n_K a Monte Carlo path in the construction phase at a given time.

A2.1 Expected Cash Flows and Cost-to-Completion (Forward-Looking Monte Carlo)

A full set of paths out to the defined end of the simulation were generated for expected construction costs and revenue. The model simulates revenue flows out to final time step, T, which is set at 30 years (120 quarters or model time steps) longer than the combined time of the licensing process and license duration in order to capture construction times of up to 30 years. While the stochastic process for construction time could ultimately lead to a construction project of unlimited length, the probability of encounter a project with an actual duration of longer than 30 years is minimal.

To simulate revenue, electricity price is first defined recursively. Then this electricity price is plugged into the (otherwise non-stochastic) random determination of the free cash flows:

$$FCF_t = \left[(1-\tau)\left(P_t(9240-H) - O\&M(H)\right) + \tau\left(D_t(K) + PTC\right)\right]\Delta t$$

During the COL process ($t \le T_L$) no technical uncertainty is resolved, and construction costs only evolve (discretely) as:

$$K_t = K_{t-1} e^{\left((\alpha_{ic} - \sigma_{ic}^2)\Delta t + \sigma_{IC}\sqrt{\Delta t}\right)}$$

Meanwhile licensing costs evolve accordingly as an arithmetic Brownian motion:

$$L_t = L_{t-1} - I_L \Delta t + \sigma_L \sqrt{\Delta t}$$

During construction ($T_L < t \le T_L + T_K$) Input cost uncertainty resolves with investment, input costs have been fixed at T_L and the path tends towards $K = 0$ with bang-bang investment rate, I:

$$K_t = K_{t-1} - I_K \Delta t + \gamma (IK)^{\frac{1}{2}} \sqrt{\Delta t}$$

A2.2 Expected Value and Optimal Abandonment (Backward-Looking Least Squares)

Once a full set of licensing, construction, and cash flow paths have been simulated, the model begins at the final time step, T and rolls backwards, updating the expected value of the project for each time period t and path n, $W(n,t)$:

$$W(n,t) = \begin{cases} e^{-r_{FCF}\Delta t} W(n,t+1) & t > T_{COL} \\ e^{-r\Delta t} W(n,t+1) + FCF(n,t) & T_K < t \le T_{COL} \end{cases}$$

This continues until the model reaches T_K, at which point the expected value of the project, contingent upon the current expected remaining construction cost and current electricity price (with seasonal elements removed), is estimated using a regression run on those paths which are still under construction, n_K, such that:

$$e^{-(r+\lambda)\Delta t}W(n_K, t+1) = \alpha + \beta f(K, C) + \epsilon_{n_K}$$

Where $f(K, C)$ is a set of basis functions[14] combining elements of K andP_t, α is a constant, β is a vector of coefficients for the basis functions, and ϵ_{n_K} are the individual residuals of the regression paths. Using the parameters of this regression, the conditional expectation, $\widehat{W}(n_K, t)$ is generated as the fitted prediction. Then:

$$W(n,t) = \begin{cases} 0 & \widehat{W}(n_K, t) - I\Delta t < 0 \\ \widehat{W}(n_K, t) - I\Delta t & \widehat{W}(n_K, t) - I\Delta t > 0 \end{cases}$$

That is, when the expected value of continuing the project (continuing to invest at I) is negative, this time period is an optimal abandonment period for that path. Then, the model records this time as the earliest optimal abandonment time, and continues its recursion backwards until it reaches the final period of the COL process, T_L. At this point the regression procedure is identical, but the expected value of continuation is based off of a continuation of the licensing process at expenditure rate l instead of construction at I.

A2.3 Application of Abandonment Rules and Option Valuation

With the earliest point of optimal abandonment recorded for each simulation path, the model runs forward through the paths calculating the discounted net cash flows and cancelling the construction project if it reaches an abandonment point. These cash flows are then averaged to find the option value, F, of beginning the nuclear COL and construction process. Mathematically:

$$F = \frac{1}{N}\sum_{n=1}^{N}\sum_{t=1}^{T}\left[\left(\prod_{j=1}^{t} e^{\delta(n,t)}\right) * V_n(n,t)\right]$$

Where for path, n, at time step, t, $\prod_{j=1}^{t} e^{\delta_n(t)}$ is the cumulative multiplicative discounting parameter based on discount rate $\delta(n,t)$ which is determined by the project status of the specific path at that specific time step. $V(n,t)$ is the cash flow (licensing/construction outlay or revenue) for n at t.

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[14] The basis functions are Laugerre polynomials of order five of the state variables and the cross product of the first three polynomials of each. Other orthogonal polynomials (Hermite and Legendre) and monomials give similar results.

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