White Paper

Rediscovering the Economics of Nuclear Power

1. Introduction

Energy policy can often be narrow and take a short-term view as well as beholden to public opinion as demonstrated by the early decommissioning of nuclear power plants (NPPs) in Germany and Belgium after the Fukushima Daiichi event. The subsequent pursuit of renewable electric power generating capacity should not lose sight of the value of technological diversity in an energy portfolio. Domestic market incentives have failed to maintain the U.S.'s technological diversity as demonstrated by the dwindling state of the nuclear power industry. The nuclear power industry faces many challenges, such as aging infrastructure, policy driven production disincentives, and licensing delays, which leave the nuclear power industry at a cross roads. However, there is an opportunity to identify both a socially beneficial technology mix which includes NPPs and corresponding strategies for retaining NPPs in the U.S. energy portfolio. This paper proposes three technical approach options to identify strategies to assist NPPs that will hopefully prove publicly unobtrusive, economically affordable, and potentially profitable.

2. Problem Statement

The current economic situation for NPPs is extremely challenging due to multiple market failures that do not appropriately incentivize investment in nuclear power. Low cost natural gas, subsidized renewables, construction cost overruns, and a lack of credit for supplying low emission electricity have driven the US into an economic climate in which existing NPPs are prematurely closing and the VC Summer AP1000 construction activities are being abandoned. One major challenge to economic viability of NPPs is their long-associated time horizon. Design and licensing can take decades and then most plants need to operate for decades more before they can recoup their investments. During this time, the electrical market can change and new policies can be implemented which can invalidate a given NPP market assumptions. To further complicate the economic picture, NPPs face significantly different economic forces when operating in regulated and deregulated markets. Deregulated utilities face the most significant pressure to decommission their existing NPP fleet.

U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration
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The total amount of electricity consumption in the U.S. is approximately 4,000 TWh. This consumption has been constant for approximately 10 years and is not expected to deviate much in the foreseeable future due to demand side technologies. The fundamental shift in installed capacity in the U.S. towards natural gas (NG) at approximately 34% and renewables at about 15% leaves the remaining electricity grid in need of additional sources of reliable and large capacity generation. Current installed capacity for coal at 30.4% (generating 500 MW per large plant) and nuclear at approximately 20% (generating 1,200 MW per power plant unit) are ideal candidates for providing capacity while also ensuring base load and high reliability. Coal plants may be quick and cheap to build, however, coal's capacity factor (CF) is only around 33% while nuclear power can reach 100% CF. The cost structure of nuclear power has remained mostly unchanged. That is, the lifetime-levelized costs of nuclear electricity production are dominated by capital costs. The cost breakdown is roughly: 66% capital investment, 20% operations and maintenance, and 14% fuel-related costs.

Plans for new NPPs began in the early 2000s to decarbonize U.S. electricity generation and the improving economics of nuclear power against high hydrocarbon prices. Public policy played a role in the U.S. utilities interest in NPP construction. The US Energy Policy Act of 2005 provided for federal loan guarantees for various energy technologies as well as a degree of insurance and production tax credits for the first six GW of nuclear plant capacity.[1] The hope was that a "nuclear renaissance" could replace the current aging fleet as well as provide additional generation capacity. Recently, two South Carolina electric utilities announced their intent to cancel a decade long project to build two new NPPs in Fairfield County. One threat to the projects was severe project mismanagement. Another threat was the loss of tax credits due to construction delays. It is argued that an extension of these credits could salvage the project and promote additional construction.

The fundamental question for promoters of the nuclear industry such as the DOE remains: How should the U.S. government most effectively promote the commercial NPP industry in a complex and changing electrical market when previous interventions have been only partially successful?

3. Creative and Innovative Nature of R&D

Only by understanding the complex market interactions between the NPPs and the rest of electrical grid can the impact of optimal market incentives be evaluated. Sandia's existing capabilities address many technical components of the electric power infrastructure. The proposed work couples small-scale micro-grid engineering with economy-wide load and economic systems models to formally link technology limitations to energy mix forecasts.

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[1] Department of Energy 2005 SEC.1306 and 1703

4. Proposed R&D

Table 1 describes three technical approaches that can be taken in FY18. They are ordered from least to most resource intensive. All proposed options evaluate key tradeoffs associated with policy choices that impact the nuclear industry. More detailed studies will evaluate how these tradeoffs dynamically change when they are exposed to evolving economic landscapes.

Table 1: Technical Approach Options

Option Name	*Brief Description*	*External Engagement*	*Cost*
Landscape Survey of NPP Options	Provides a quick assessment of what market conditions need to be achieved to support the current fleet and recommendations on how to reach those conditions. Limited time horizon (<5 years) and its insights quickly become outdated.	Extremely limited.	$400K
Rigid but Dynamic NPP Economics Futures Evaluation	Leverages pre-existing models to address a predefined set of marketplace options. This project can be updated to account for small to intermediate changes in market conditions. Not flexible to changing project scope or new technologies.	Internal and external partners.	$700K
Adaptive and Dynamic NPP Economics Model	Multi-decision criterion analysis (MDCA) using a system dynamics (SD) approach to tie together critical market forces that will allow for evaluations of how various potential futures impact the economic viability of NPPs.	Multiple organizations.	$1.1M

Option 1: Landscape Survey of NPP Options

This option will leverage heavily off pre-existing tools (e.g., ReEDS)[2] and studies and will examine how various policy actions or market forces may impact NPP retirements and construction within the next five years. The generic market approaches of various operating and proposed reactors will be surveyed and evaluated to determine their types of market environments that will be needed for their commercial

[2] https://www.nrel.gov/analysis/reeds/

success. Additionally, a tradeoff analysis will be performed to compare financing option for investments in stalled projects. The attributes of a tradeoff analysis may include:

- Normal source financing: financing for private sector investments, consists of borrowing or raising equity against the assets of the company.
- Project financing[3]: Key feature of project financing is that a new company (known as a special purpose vehicle (SPV) or special purpose entity (SPE)), which can be considered the project company, is set up solely for owning the project to be built.
    - A bank or consortium of banks then lends to this project company, which in turn owns the asset, which we will assume is a power station or NPP.
    - As the loans are made to the project company, not the sponsor company wanting to build the station, they are said to be "non-recourse" to the sponsor.
- Regulatory Options: evaluate if and how the regulatory process could proceed without impeding development, construction, siting, and life extension of NPPs.
- Political Risk: NPPs suffer from a public acceptance problem. Educating the public on the relative low-carbon, generation capacity, and actual safety has the potential to lower the hurdles for completion of construction projects for NPPs.
    - There is significant research in energy economics that proves that consumer's interest in the environment has led utilities to seek wind and solar PV as generation sources. That is, the demand has influenced the sources of supply because industrial customers have more market power.

The impact of each landscape on NPPs on regulated and unregulated markets would be evaluated separately. Due to the lack of detailed model development from this study, the impact of market disruptions that are experienced midway through the study will be difficult to incorporate into the final survey findings.

Option 2: Relative Trade Study

This option will adopt techniques described in the *Landscape Survey of NPP Options* but will modify the exiting tools to examine longer term policy objectives. These analyses will provide deeper insights to the questions from Option 1 and bring in a wider set of external partners, data sources, and feedback to ensure that the study is encompassing of the current electrical market forces. By modifying existing

[3] "financing the development or exploitation of a right, natural resource or other asset where the bulk of the financing is not to be provided by any form of share capital and is to be repaid principally out of the revenues produced by the project in question" (Vinter 1998)

models, this study takes many of the tradeoff analyses explored in Option 1 and extends the time horizon to include the relative market forces that are expected to impact NPPs over the next 10 years.

Production cost models will be employed to evaluate the installation of generation III+ and IV NPPs (referred to hereon as NexGen NPP). These facilities are predicted to have very different demands for water and both fixed and variable operating and maintenance (O&M) costs. Currently O&M for NPPs is $6 per watt for a plant ranging 1,200-2,000MW generation. NexGen NPP have potentially very different construction and O&M costs providing an opportunity to apply new financial models, incentive structures, public buy in, and perhaps even new regulatory model. The arena examining NexGen NPP is in line with many of the future goals of the utilities and generators, which is a future system built more on distributed generation and transmission. For these utilities, the fundamental question is the price of electricity and the fundamental components of the electricity cost. The earnings of a utility are fundamentally linked to quantifiable performance metrics, baseload and reliability, which remains a challenge for renewables. There is an incentive for utilities to seek out the most reliable generation sources with high CF, however, these must align with reasonable rates for customers. This gets at a fundamental question of what are customers willing to pay to have access to safety or access to reliable low-carbon electric power.

This analysis would need to include the impact of relatively large electrical market inertial forces. The electric power industry is approximately 3% of GDP representing a considerable portion of the nation's output and promotes itself as being open to the adoption of new technology and spurring down-stream economic growth. It is possible that the AP1000 tax incentives did account for the long lag time associated with the construction of NPPs and thus was not able to adjust to changing market forces. Industry would argue that lags in adoption of new technology often arise from policy short-sightedness and regulatory constraints. Policy actions will likely fail without understanding the impact of these lags.

To ensure quality insights, the final set of policy questions which will be examined will need to be determined at the beginning of the study. Because some model development will occur during this study, the impact of market disruptions that are experienced midway through the study can be incorporated into the final survey findings.

Option 3: Software Tool

This option will define and evaluate a suite of parametric scenarios assessing required changes to infrastructure (grid, energy storage, water, fuel substitution/delivery) in response to energy mix evolutions, for example:

- NPPs for Coal: maintain current nuclear capacity while phasing out coal-fired generation.
- NPPs as a Bridge: expanding NPPs (3rd and 4th generation tech) can either assist or delay the expansion of alternative fuels while phasing out coal-fired plants.

- NPPs replace the current wave of NG: An initial wave of NG plants has been built as NG prices dropped in the early 2010s with a lifetime of approximately 30 years. Necessary market conditions that facilitate NPPs to replace these generators.
- Off-grid NPPs: US nuclear capacity shifts from baseload power generation to off-grid or micro-grid applications that typically experience higher marginal electricity costs.
- What NPP grid behaviors should be prioritized: Advanced reactors and power conversion cycles can potentially allow for new modes of operation on the grid. What operational modes would be most economically competitive, e.g., load following.

To identify and assess these options, a model is needed that is robust enough to adapt to changing conditions in real time and will not need to be completely rebuilt when the next market shift occurs. The optimal approach will incorporate additional expertise from throughout the laboratory. The field of Multi-Criteria Decision Analysis (MCDA) extends the field of Decision Analysis, which was employed by the Fuel Cycle Options Study[4], by providing a collection of methods by which trade-offs can be made across performance criteria or Indicators of Impact (IoIs) beyond utility and monetary based measures. MCDA methods generally contain similar structural elements including: objective(s), several alternatives, a set of criteria in which the alternatives are assessed, and weights placed on criteria (i.e., IoIs) that represent the relative importance or preferences.

This software tool will be used to develop a parametric analysis of the technologically-viable solutions (e.g., infrastructure requirements, electricity production technology limitations) to increase the share of NPPs in the U.S. electricity grid over the next 30 years. Per the 2017 DOE/NE vision and strategy document[5], by 2030 at least two fourth-generation, non-light water, reactors will have begun construction. This goal will be difficult to achieve if the correct market forces are not in place.

For the proposed MCDA Model, SNL will first develop the capability to identify underlying constraints on expanding NPPs electric power generation role in the US economy. IoIs will be developed to measure the consequences of such expansion on the economy, electric power (EP) dispatch-ability, grid stability,[6] base-load effects, the environment, security and power availability of nuclear, coal, and renewable fuel sources. Research from the Paul Scherer Institute (PSI) on the sustainability of energy supply in Germany identified 18 such indicators when comparing different energy mix options.[7] Because the software tool

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[4] Wigland, Roald, et al, "Nuclear Fuel Cycle Evaluation and Screening – Final Report," FCRD-FCO -2014-000106, INL/EXT-14- 31465, October 8, 2014.

[5] Vision and Strategy for the Development and Deployment of Advanced Reactors, Department of Energy: Office of Nuclear Energy, DOE/NE-0147, Feb. 2017.

[6] Silva Monroy, C.A. et al., 2013, A Set of Representative Scenarios to Address the Grid Integration of Renewables, INFORMS Analytics Conference.

[7] Hirschberger, S., Spiekerman, G., Heck, T., Burgherr, Schenler, W., and Burgherr P. (2004), Comprehensive Assessment of Energy Systems (GAbE) - Sustainability of Electricity Supply Technologies under German Conditions: A Comparative Evaluation. Paul Scherer Institut, Switzerland.

option is explicitly intended to capture dynamic evolutions in the energy market and downstream impacts on NPPS, this option provides the greatest flexibility to reassess changing conditions on prospective and retrospective analyses.

5. Relationship to Prior and Other On-Going Work:

Outside of SNL, multiple economic studies of NPPs can be leveraged to ensure an encompassing study of how NPPs can be made economically competitive in the future. The Massachusetts Institute of Technology (MIT) is currently well into their latest revision of the Future of Nuclear Power Study, the participants and insights from the MIT study can be leveraged to ensure that the conclusions of both studies are as robust as possible. Colorado School of Mines Department of Economics has been at the forefront of energy economics for decades and studied the causes of NPP construction overruns. SNL also has strong ties to NREL's Energy Systems Integration and thus is uniquely positioned to lead a partnership with the Joint institute for Strategic Energy Analysis.

The work proposed here looks to build from these experiences in model architecture and topical expertise to abstract up from engineering models to the systems-level models.

6. Goal and Success Measure

Once created, the Option 3 MCDA SD software tool capability can be used to inform tradeoff decisions for national conversations on the future of nuclear power supplies and the evolving US energy mix. This process will directly identify the R&D and policies required for technology innovation in supply, delivery, and/or end use of NPP, ensuring a minimal environmental impact and assuring cost effectiveness. Our aspiration is to create a tool that informs choices about our national energy future for production and technology investments as well as economic and environmental national security.

Outputs in the research area will consist of leading edge publications, data, conference presentations, and a deployable tool and technical basis for up and downstream energy companies, and public agencies (e.g, DOE, DHS, DOD). Publications and conference presentations will be interim and final results. A final and important result will be to provide policy guidance for the future growth of the nuclear power industry.

7. Leveraging Results

We will actively leverage the aforementioned projects which examined the economic drivers in grid and energy systems to provide inputs and supplemental insights to this analysis. Additionally, this research will become available to other groups throughout Sandia to leverage their clients (e.g., disruption events at Nuclear power stations would have dramatic impacts on grid and load balancing stability), as well as potential external engagement partners (e.g., Southern Company, Rice University, Stanford University).

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