Studies in Nuclear Energy: Low Risk and Low Carbon

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Table of Contents

Table of Contents - Continued

Table of Contents - Continued

List of Figures - Main Body

Figures - Chapter 2 Page

Figures - Chapter 3 Page

Figures - Chapter 4 Page

Figures - Chapter 5 Page

List of Tables - Main Body

Abstract

The amount of greenhouse gas emissions mitigation required to prevent the most dramatic climate change scenarios postulated in the 2014 IPCC Synthesis Report is substantial. Prior analyses have examined the potential for nuclear energy to play a role in decarbonizing the energy sector, one of the largest contributors to emissions worldwide. However, advanced, non-light water reactors, while often touted as a viable alternative for development, have languished. Large light water development projects have a repeated history of extended construction timelines, re-work delays, and significant capital risk. With few exceptions, large-scale nuclear projects have demonstrated neither affordability nor economic competitiveness, and are not well suited to nations with smaller energy grids, or to replace fossil generation in the industrial process heat sector. If nuclear power is to play a role in decarbonization, new policy and technical solutions will be needed.

In this manuscript, we examine key aspects of past performance across the nuclear enterprise and explore the future potential of nuclear energy worldwide, focusing on policy and technical solutions that may be needed to move nuclear power forward as a part of a low-carbon energy future. We do so first at a high level, examining the history of nuclear power research and development in the United States, the nation that historically has led the way in the development of this generating technology. A significant portion of our analysis is focused on new developments in this technology – advanced non-light water reactors and small modular reactors. We find that while there are promising technical solutions available, improved funding and focus in research and new models of deployment may be needed if nuclear is to play a continuing or future role. We also find that in examining potential new markets for the technology, a continuing focus on institutional readiness is critical.

CHAPTER 1

1. Research Context.

One of the greatest challenges facing earth's environment is the continued emission of greenhouse gases (GHG) resulting from the use of fossil fuels as our primary source of energy. To address this challenge, increased effort to deeply decarbonize the energy sector, which accounts for approximately 35% of GHG emissions in most nations,(1) will be required. This effort will become even more crucial if climate change mitigation efforts lead to a more electrified society.(2)

In decarbonizing the energy mix, most agree that the entire range of carbon-free generating technologies should be considered.(3) It is clear that renewable generation will continue to grow, especially as solar and wind technologies become more cost-competitive. However, renewables are not well suited to some locations and cannot effectively meet all energy demands (especially industrial process heat applications). They can also lead to grid stability and energy security concerns if deeply deployed. Nuclear fission is currently one of the largest carbon-free generating sources and is a likely candidate for dispatchable low-carbon generation as a part of the future energy mix. It has a high capacity factor (a measure of full power operating time), can be deployed at scale, and does not lead to the stability and reliability issues associated with variable and intermittent power sources. But nuclear power faces many challenges. Since the mid-1990's, nuclear energy's contribution to overall world generation has decreased by almost 7% while renewable generation, which many hope will expand quickly to meet new generation need, has only increased by about 4.5%.(4) If this trend continues, it will significantly complicate efforts to maintain less than a 2°C rise in global temperatures.

The reduction in nuclear power's contribution has been driven by many factors. New nuclear developments have been plagued by high construction costs and cost overruns, especially in the U.S. and Europe. (5) Development continues to depend on a civil engineering project model, focused on building ever-larger light water plants. While small modular reactors (SMRs) have been studied extensively and may hold promise for a product based development model, there has been little movement toward broader deployment of these designs. Existing plants are under scrutiny and stress in many developed countries due to safety concerns following the accident at Fukushima, Japan and poor economic competitiveness with other forms of generation. This has resulted in the early shutdown of a number of plants in the U.S. and Europe.(6) Advanced non-light water nuclear technologies that may further enhance safety, reduce waste, limit proliferation risk, and improve economic competitiveness have languished, in part due to unfocused and underfunded research and development (R&D). If nuclear power is to play any significant role in the decarbonization of the energy sector, these challenges must be overcome. Development and implementation of a comprehensive set of technical and policy solutions will be needed to minimize further reductions in the current fleet and ensure that by mid-century, new technologies and new development methods are mature and available for broad deployment.

2. Dissertation Overview

In this dissertation, we examine key aspects of past performance of the nuclear enterprise and explore the future potential of nuclear energy worldwide, focusing on policy and technical solutions that may be needed to move nuclear power forward as a part of a low-carbon energy future. We do so first at a high level, examining the history of research and development in the United States, the nation that historically has lead the way in the development of this generating technology. A significant portion of our analysis is focused on the new developments in this technology that have recently come into view – advanced non-light water reactors and small modular reactors.

We open our review with a quantitative assessment of research and development that is based on over 40 years of federal budget data, obtained through the Freedom of Information Act (FOIA) from the U.S. Department of Energy (DOE). Our analysis indicates that despite over $2 billion expended on advanced reactor research and development activities in the last twenty years by the DOE Office of Nuclear Energy (NE), no design is remotely ready for deployment in the U.S. We find that absent a sense of urgency within NE—one that engenders the funding and focus required to develop and deploy a new nuclear technology—the likelihood that advanced reactors will play a substantial role in the transition to a carbon-free U.S. energy portfolio in the next thirty years is exceedingly low.

In our third chapter, we explore further the dysfunction in the U.S. advanced nuclear enterprise. This section reports the results from interviews we conducted with thirty nuclear energy veterans—all with extensive knowledge of the DOE Office of Nuclear Energy and the history of nuclear technology development—to elicit their impressions of the state of nuclear innovation in the U.S. and its likely future prospects. The interviewees were drawn from across the nuclear enterprise, including representatives from major nuclear vendors, academia, government, and the national labs. Most reported few noteworthy successes in advanced nuclear research and development over the last twenty years due to a lack of political support and poor focus. However, there was limited agreement regarding the best way forward. Even with aggressive assumptions, the experts indicate that advanced nuclear technology is unlikely to play a role in the timeframe necessary to deeply decarbonize the energy system. A new approach to research and development will be needed if the U.S. is to remain relevant, not just in the nuclear marketplace, but also in the international safety and governance realm for this technology.

In our fourth chapter, we begin to examine the potential for nuclear more broadly, examining the expansion of nuclear development worldwide. If new technologies such as SMRs are to play a role in the decarbonization of the energy sector, vendors must see a demand and market for these systems. Vendors and regulators must also understand the risk associated with development in non-nuclear nations. A key factor in the assessment of readiness for nuclear development is institutional capacity. In taking on the complexities of nuclear development, nations must be prepared to manage the safety, security, and proliferation risks inherent in the technology. Utilities and vendors must understand the financial risk associated with development in these nations. In this chapter, we examine the market for SMR technology, with an emphasis on institutional performance using a benchmarking technique – data envelopment analysis (DEA) – to evaluate development readiness. We find that while there is a potentially large market for the technology, the vast majority of it still resides in existing nuclear nations. We also find that if institutional factors hold sway, the market size may shrink significantly.

While it may be possible to build the capacity of some nations to support nuclear development, for decarbonization the emphasis must still remain on the largest GHG emitters, the vast majority of whom are already nuclear nations. As a sensitivity analysis in this section, we also explore the potential for a different deployment model known as "build-own-operate-return (BOOR) following a unique technical solution – a floating small nuclear power plant. We find that there may be a viable market for SMR technology that may aid in expanded use of nuclear power as a low-carbon energy solution following the floating BOOR model, especially in nations with growing economic and institutional capacity but perhaps more limited technical and human capital capabilities. Chapter five examines this concept more fully.

The notion of floating nuclear power plants is not a new one, having been explored in detail in the 1970's. Recurring cost and schedule challenges in the development of light water reactors have lead to a re-examination of alternatives such as a floating plant as a means of controlling development in a shipyard manufacturing environment and as a way to mitigate other accident risks such as earthquake and tsunami. In this final chapter, we explore this option which brings with it the potential for use of the BOOR model as an option for deployment beyond the existing cadre of nuclear nations. The BOOR model in this instantiation involves an advanced supplier nation building, owning, and operating a fleet of small modular nuclear reactors (SMRs). These SMRs would be sited on offshore platforms, and their power transmitted to host nations via undersea power cables. Once their fuel is spent, they would be returned to a centralized facility for refueling and waste processing. These floating small modular reactors (fSMRs) might mitigate some of the risks associated with land-based reactors, enhancing safety and economic viability, while the BOOR model should help to reduce the material proliferation risks. Our assessment includes the development of a modeling tool that can be used to evaluate the costs associated with fSMR development as compared with terrestrial development. We find that despite having the substantial benefits of a nuclear fuel cycle that is managed by existing nuclear-capable states, increased scope for cost control, and more limited risk of exposure in the event of an accidental release of core inventory, floating nuclear power plants would cost 1.5 to 2 times as much as equivalent, land-based sites if the former are built to stringent, quasi-

U.S. military specifications for steel, welds, and quality assurance assuming no significant cost overruns are incurred for the land-based plants. Nuclear technology vendors pursuing this option commercially must recognize that, through a combination of prudent risk avoidance and regulatory caution, they would likely have to contend with satisfying both nuclear and quasi-military design specifications, incurring a substantial cost premium over alternate generation options. Despite these risks, development of this option is being pursued in nations such as China and Russia. Given this, we recommend an international regulatory assessment to (1) establish standards for fSMR development and deployment. The International Atomic Energy Agency, International Maritime Organization and the United Nations should establish guidelines for platform construction, evaluate accident liability regimes and establish transportation, security and proliferation protocols for vendor and host nations. (2) Incorporate a floating siting option into ongoing international regulatory assessments of SMR and advanced reactor design licensing processes.

Chapter 1 References

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CHAPTER 2

A retrospective analysis of funding and focus in U.S. advanced fission innovation

1. Introduction

Substantial scholarship has emerged around the need for radical innovation in energy technologies in order to reduce emissions and stabilize the climate.(1,2) Along with recommending a large increase in public sector spending on fundamental innovation and early deployment,(3-5) this work has also emphasized the need for a wide array of technologies, including nuclear power(6). Here we focus on a particular type of nuclear power—advanced, non-light water reactors. For the study of energy innovation, nuclear power is particularly interesting because there is a history of efforts to invest in new designs, and that history can reveal how the public sector may need to reorganize its efforts to innovate.

Energy planners have long envisioned a nuclear enterprise in which advanced, non-light water reactors would safely operate for decades and burn up most of their fuel.(7 -12) If this future is ever to materialize in the U.S., it will require the support of the Department of Energy's (DOE) Office of Nuclear Energy (NE), which is charged with catalyzing nuclear fission innovation.(13) However, despite repeated commitments to a non-light water future(14-17) and substantial investments by NE, no such design is remotely ready for deployment today.(18)

Once the global leader, the U.S. pioneered several non-light water concepts in the first two decades of the atomic age,(9) and constructed large-scale demonstrations that operated well into the 1980s.(11,12) High cost and disappointing performance, together with the commercial commitment to light water reactors (LWRs), deflated interest in advanced designs in the 1990s.(12) The nadir of support came in 1998 when NE's research activities were defunded, and its budgetary role was limited to facility maintenance.(19) Over the past two decades, growing concerns about climate change, the imminent retirement of a significant fraction of the current fleet of LWRs and the limitations of LWR technology,(20) have led to a resurgence of interest in non-light water reactors. As a result, NE has made new investments in a number of non-light water initiatives. Here, we investigate how effectively those resources have been allocated, and how NE has performed as a steward of nuclear technology innovation.

2. The role of government in innovation

Classically, the role of government in technology innovation is to support fundamental research and development (R&D);(21,22) applied R&D offices like NE are expected to fund potential breakthrough technologies at the early stages of technological readiness.(22,23) This paradigm is based on the assumption that industry will eschew high-risk, high-expense, or long-duration research, focusing instead on more proximate and proven activities that maximize the net present value of its existing revenue streams. In Figure 2-1, we display these roles in a continuum, acknowledging that some projects require a partnership between government and industry.

In analyzing the performance of NE, we first determine the amount of funding advanced reactors have received since 1998, down to the level of fundamental R&D at the national laboratories. We then analyze the lifecycle of NE's major programmatic initiatives, to determine whether its funding priorities are stable or erratic. We focus on the period from 1998 to 2015 because it presents the full spectrum of funding support, from the nadir, when it appeared work on advanced designs would be eliminated, through a period when political interest in the promise of nuclear energy peaked.

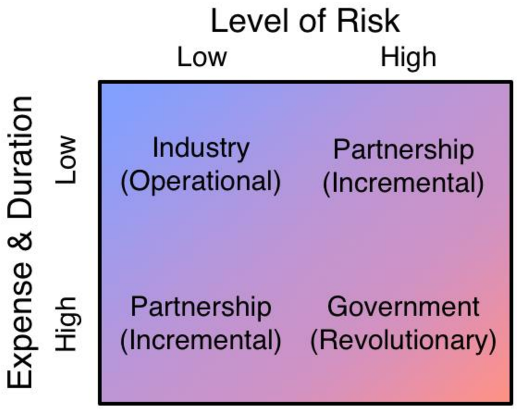

Figure 2-1: Classical roles of industry and government in innovation. Generally, government is expected to support fundamental R&D or potential technological breakthroughs that are at a low level of readiness. Industry is responsible for operational innovations that sustain and optimize its revenue base.

Once it became clear that its elimination was not going to be permanent, NE began developing a technology strategy that included DOE's twenty-first-century vision for advanced reactors. Released by its Research Advisory Council in 2001, it laid out a path for deploying new reactors as a logical and desirable follow-on to existing LWRs.(16) Starting in 2002, NE released roadmaps that outlined how it would prosecute this strategy and start building an advanced, non-light water design in 2017.(14-18) While these roadmaps catalog NE's progress in advancing the designs it supports, and occasionally provide timelines for eventual deployment, they rarely provide a systematic analysis of how to achieve NE's objectives.

To analyze progress since these roadmaps were published, we compiled annual DOE budget justification documents, going back to the department's founding, which detail funding down to the level of individual programs. These were secured through Freedom of Information Act (FOIA) requests. We then reviewed annual laboratory-directed research and development (LDRD) budgets—these are national laboratory projects selected through a competitive process and dedicated to cutting-edge, high-risk R&D(24)—that describe this research by laboratory, project name and funding level. For both the justification documents and the LDRD reports, each budget line item was classified as one that supports LWRs, advanced reactors, or crosscutting technologies – which are those that would support both light water and non-light water development. Next, we investigated the lifecycle of NE's major programmatic initiatives.

While existing literature presents some elements of DOE's budget at a macro level, this detailed review of NE's budget constitutes our key contribution. Prior reviews have commented on the "opaque" nature of DOE budget documentation.(25) We initially faced similar challenges, but eventually managed to reconstruct how NE's budget line-items have evolved since 1998. All values reported in this paper have been converted to real 2014 dollars.

3. Placing the Office of Nuclear Energy's budget in context

Since 1998, DOE's budget has been between \$23 and \$29 billion, save for 2009, when it increased to \$37 billion as a result of the stimulus package that increased spending across many government departments. As illustrated in Figure 2-2a, a substantial portion of the DOE budget goes to non-R&D activities and program direction. The portion dedicated to R&D has fluctuated between 50% (2009) and 66% (2015). In turn, most of that is dedicated to “non-energy” activities, notably managing the nuclear weapon stockpile (“non-energy R&D” in Figure 2-2a). Since 2000, these activities have come under the purview of the National Nuclear Security Administration (NNSA), and have consumed $8 to $11 billion of the annual DOE discretionary budget, their share varying between 55% (2009) and 69% (2005) of R&D spending. The $3 to $5 billion per year that DOE has spent on “Energy Programs” constitutes 10% (2005) to 16% (2008; 2010) of its annual budget.

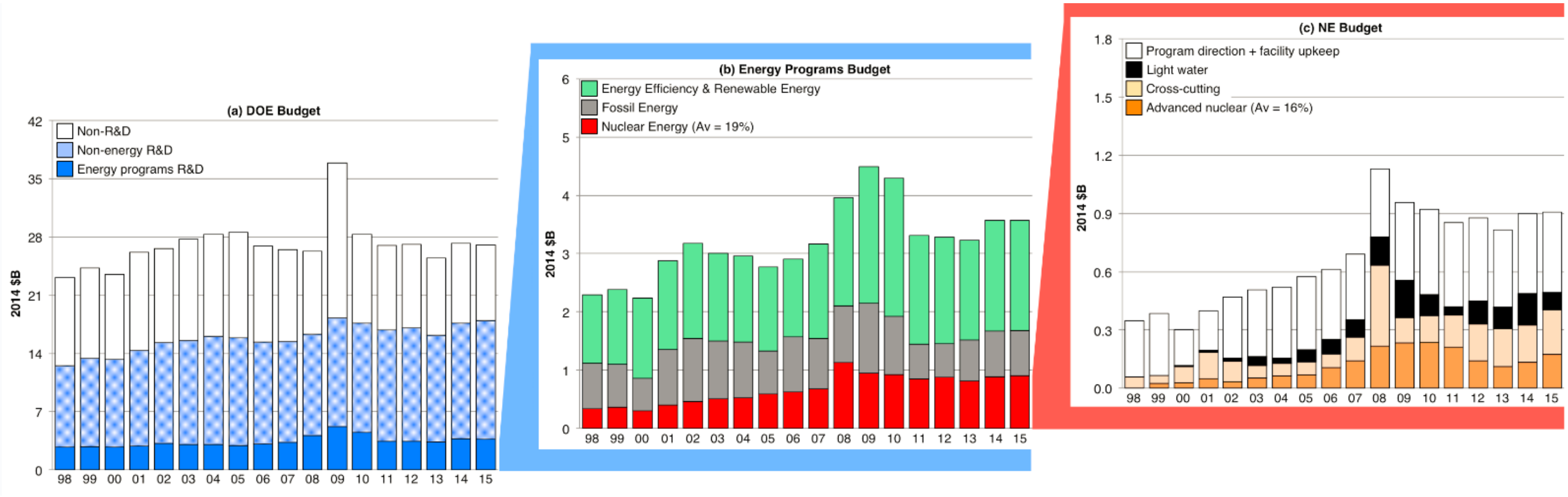

Figure 2-2: Calculating the level of funding for advanced reactors. (a) The portion of DOE's discretionary budget that is dedicated to R&D in general (light blue) and energy R&D in particular (dark blue). **(b)** The portion of the energy R&D budget that is dedicated to the Office of Nuclear Energy (NE, red). **(c)** A breakdown of NE's budget in terms of its support for advanced reactors, crosscutting technologies (such as simulation capabilities or fuel cycle research), light water reactors and program direction and facility upkeep.

Most of the “Energy Programs” budget is divided among three offices, shown in Figure 2-2b: along with NE, there is the Office of Energy Efficiency and Renewable Energy (EERE) and the Office of Fossil Energy (Fossil). Over the period we studied, NE averaged 19% of DOE’s energy spending, EERE averaged 49%, and Fossil averaged 25%. The money appropriated to NE annually is substantial—$670 million, on average—though, in our 18-year sample, it fluctuated by a factor of four between a minimum of $300 million in 2000 and a maximum of $1.1 billion in 2009.

Not all of NE's money is dedicated to the development of paradigm shifting technologies, such as advanced reactors. In fact, the office’s activities can be broadly divided into three categories: first, sustaining the reliability and safety of the current LWR fleet; second, developing and deploying new fission technologies that promote nuclear power’s viability; and third, maintaining infrastructure that enables the execution of DOE’s weapons, non-proliferation and nuclear research missions. Though these categories mirror NE’s primary tasks, its official mission statement and funding focus has changed frequently, arguably driven by external political factors and reflecting a lack of programmatic discipline. In Figure 2-2c, we report where NE’s research dollars have gone since 1998, demonstrating the extent of the problem.

On average, NE spends 57% of its annual budget on program direction and facility operations and maintenance, though the annual figure varies widely between 30% and 90%. On average, only 15% of its budget has been spent on aspects of advanced fission research, development, and deployment. The amount has varied between $0 and $240 million per year. Over 18 years, NE has spent a total of $2 billion on non-light water research, which is just 0.7% of DOE’s total R&D expenditure during that period. Only part of this money has gone to advanced reactors; a portion, ranging from 20% to 40% annually, has gone to research on advanced fuels.

To appreciate just how modest advanced reactor research expenditures have been, consider that recent estimates of the amount required to shepherd one advanced reactor technology through design completion and licensing exceed $1 billion; the construction of a demonstration reactor is estimated to require at least $4 billion.(18) Hence, the total investment required to bring a new design to the point where it could be commercially developed and deployed is on the order of $5 billion. Given the history of cost overruns associated with new nuclear technologies, these estimates, which were spelled out in NE's 2001 advanced reactor roadmap and in subsequent reports in 2006, 2008 and 2016,(14-18) are likely to be optimistic. By some estimates, the cost to move one design through to demonstration could "easily exceed $10 billion."(20) Either way, the total amount expended on advanced nuclear power by NE over the past 18 years—spread across multiple fuel types and technologies—has been substantially less than the investment required to ready ***one*** non-light water design for commercial deployment.

The high costs that NE incurs on program direction and facility upkeep are due to the inherent expense of maintaining nuclear infrastructure. Idaho National Laboratory, for which NE is the lead Program Secretarial Office, has many facilities that collectively consume between a third and one half of NE's annual budget. Yet it still lacks a fast flux test facility and other capabilities that are required to qualify advanced materials and fuels. While maintaining nuclear research infrastructure poses unique challenges, it is instructive to compare what NE expends on program direction and facility upkeep to that of the two other major offices that fulfill DOE's energy mission. Figure 2-3 contrasts NE's budget allocation with EERE and Fossil. While NE has spent an average of 57% on these activities over the past 18 years, Fossil has spent 20%, and EERE has spent 10%.

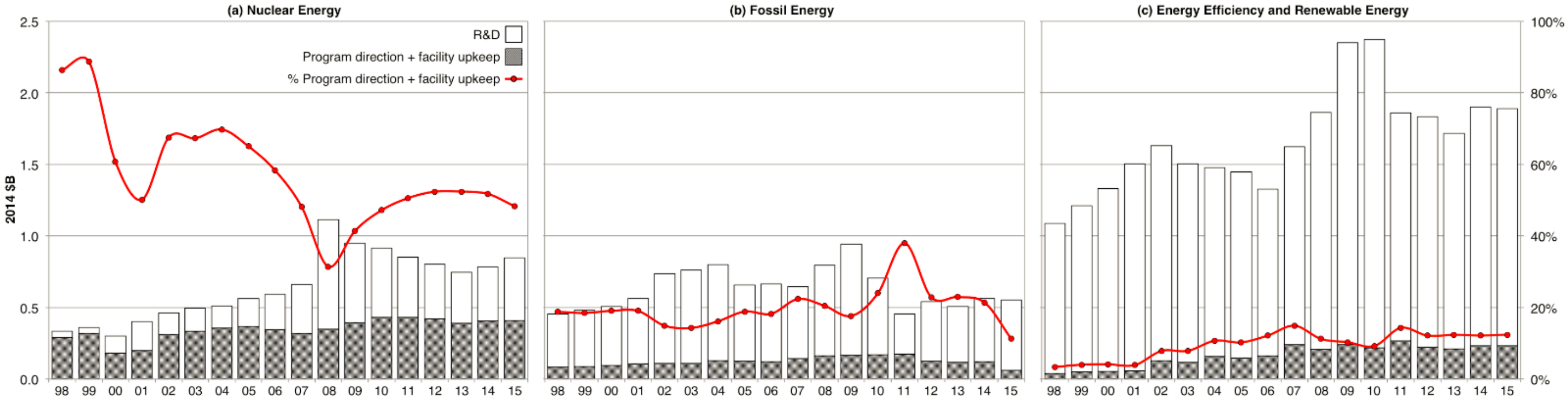

Figure 2-3: Program direction and facility upkeep in DOE's three energy offices. (a) NE spends an average of 57% annually on these tasks. **(b)** Fossil spends an average of 20% annually. **(c)** EERE spends an average of 10% annually.

4. Investigating laboratory-directed research and development

NE makes much of its investment in fundamental nuclear R&D through the national labs and explicitly highlights its advanced reactor LDRD as a pillar of its strategy to accelerate their development.(26) Four of the nation's 17 labs—Argonne, Idaho, Oak Ridge and Sandia—can be characterized as incubators of innovative non-light water research. However, Sandia is primarily a nuclear weapons lab. A further three—Brookhaven, Pacific Northwest, and Savannah River—do some fission related research but work primarily on LWRs or waste remediation.

For the three major advanced reactor labs—Argonne, Idaho, and Oak Ridge—Figure 2-4 classifies the amount of LDRD funding dedicated to nuclear energy technologies in general, and to advanced reactors in particular. LDRD funds are competitively awarded to projects that are high-risk and potentially high-reward.(24) It is only a small portion of the total budget of each lab and is limited to 6% by statute.(27) But even at this fundamental research level, these three centers of advanced reactor research dedicate little effort to non-light water reactors. At Argonne, advanced reactor LDRD accounts for an average of 1.2% of total LDRD. At Oak Ridge, the figure is 3%. And at Idaho—NE's laboratory—advanced reactor LDRD accounts for 7.5% of total LDRD. The five largest non-light water laboratories have spent a total of $47 million on advanced reactor LDRD in the past 12 years, out of total LDRD expenditures—in all 17 national labs—of $6.5 billion (0.7%). Moreover, LDRD projects dedicated to advanced reactors cover a large number of technologies. At Argonne, half of advanced reactor LDRD projects since 2004 have been dedicated to the sodium-cooled fast reactor. At Idaho, a quarter of advanced reactor LDRD projects have been focused on the gas-cooled reactor and its ceramic TRISO fuel. At Oak Ridge, a third of LDRD projects have focused on molten salt.

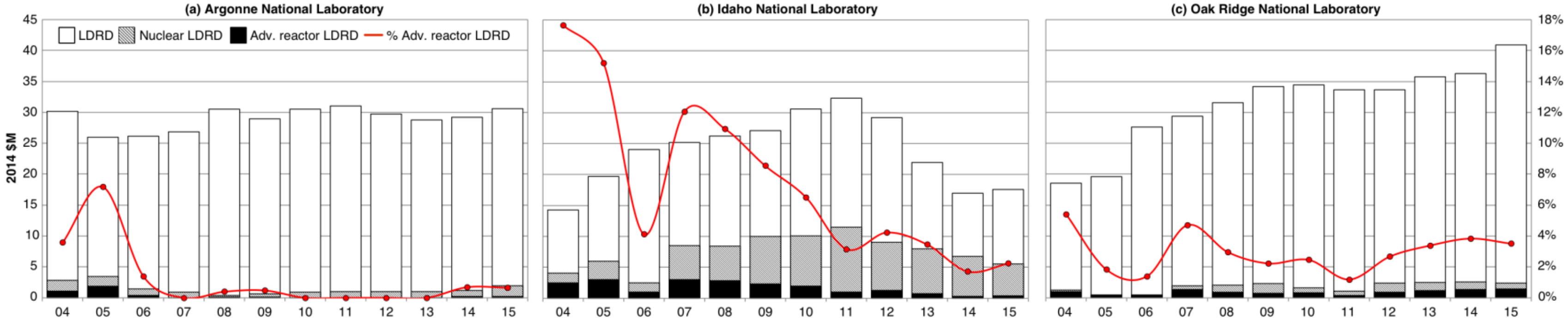

Figure 2-4: Laboratory-directed R&D on advanced reactors in the national labs. (a) At Argonne, advanced reactor LDRD has accounted for 1.2% of total LDRD over the past 12 years. **(b)** At Idaho, it has accounted for less than 8% of total LDRD . **(c)** At Oak Ridge, it has accounted for 3% of total LDRD.

5. Lifecycle of NE's major programmatic initiatives

Figure 2-5 lists major nuclear initiatives undertaken by NE over the past 18 years classified by reactor type, duration and funding level, as reported in the budget justification documents. Three points stand out. First, numerically, more than half have been dedicated to advanced nuclear initiatives (top panel in Figure 2-5): on average, these have lasted less than 5 years and cost less than $160 million each. Using DOE's own roadmaps as a guide,(14-18) these are of neither the duration nor the funding level necessary to develop a non-light water reactor.

Second, the largest sustained NE program was focused on LWRs (bottom panel in Figure 5). NP2010 began in 2002 and succeeded in supporting two LWR designs through the licensing and siting process. Vendors were intimately involved in this program, and utilities were interested in seeing viable nuclear products on the market; hence NP2010 was politically feasible. The program received a total of $750 million, 57% more than the next largest NE initiative, the Next Generation Nuclear Plant (NGNP). NGNP aimed to develop a high-temperature gas reactor to generate both electricity and high-temperature process heat for industrial applications, with construction of the first unit to begin in 2017.

Third, one reason for the mismatch between spending and mission might be rooted in bureaucratic machinations. The only advanced nuclear initiative that has succeeded in creating a "product"—which NE, as an applied R&D office, considers the ultimate measure of its success(28,29)—has been the "Advanced Fuels" program. Notably, this is the only long-lived initiative, having received over $450 million over the past 18 years, but always in installments small enough ($35 million, on average) to avoid being targeted for termination by program officers, Congressional appropriators or the Office of Management and Budget (OMB). While fuel is critical to the success of advanced designs, this program remains decoupled from reactor development. It is unclear from examining program documentation what role the fuels being developed will play in the transition to a non-light water reactor fleet.

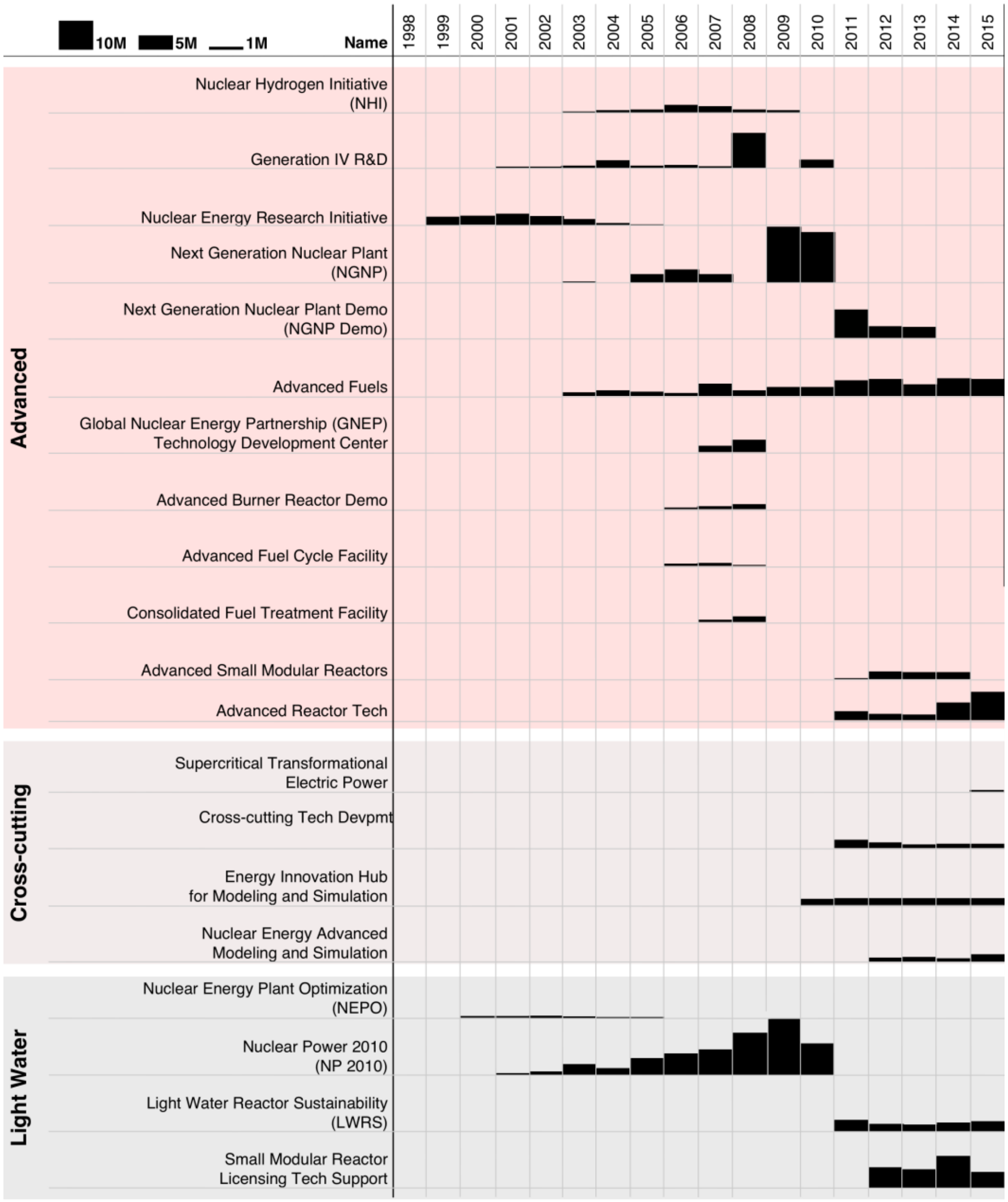

Figure 2-5: The Office of Nuclear Energy's major programmatic initiatives over the past 18 years. NE has funded advanced (top), crosscutting (middle) and light water (bottom) programs. The size of the bars reflects the amount of money appropriated to each program in each year. The mixed-oxide (MOX) plant appropriation is not included due to the distortive effect of its high cost (approximately $300 million) on figure size. Of the twenty initiatives in Figure 5, seven are ongoing. Only three of the thirteen that have ended can legitimately be considered successes, as NE defines the term: NP2010 and the Advanced Fuels program have already been discussed; the third is the smaller Nuclear Energy Plant Optimization (NEPO) program. NEPO concluded in 2005, having succeeded in enhancing the reliability and availability of the aging LWR fleet.

6. Discussion and policy implications

NE lacks the funding levels and long term commitment necessary to develop and deploy advanced, non-light water reactor designs. It has dedicated only $2 billion over the past 18 years to ***all*** advanced reactor and fuel initiatives, which by its own estimates is not enough to ready even ***one*** such design for commercial deployment. Large sums are expended to maintain research infrastructure that only marginally supports advanced reactors. Many designs are being pursued at a low level of funding, and the fuels program, while successful, is developing products that might never be commercially deployed.

NE's funding profile is not congruent with that of a successful applied R&D office. In Figure 2-6, we assign its programs to different regions in the continuum first presented in Figure 2-1. NE tries to play a substantial role in each region and spreads its money across the entire continuum.

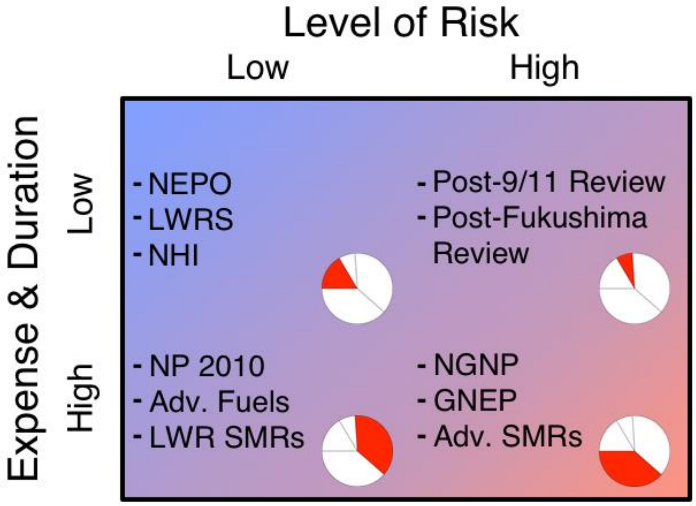

Figure 2-6: Placing the programs funded by NE on the continuum first presented in Figure 2-1. NE funds all regions of the continuum, assuming responsibility for evolutionary research that iteratively refines the existing paradigm. Pie charts reflect the portion of funding (for all programs, not just the examples given) dedicated to each quadrant of the continuum.

Moreover, substantial amounts of money have been dedicated to LWR research. Some of this is conceivably crosscutting in nature, but most probably should have been undertaken by industry, which has allowed its R&D arm to atrophy(29). Even the national laboratories—the ostensible incubators of innovation—consider it part of their mission to iteratively improve the safety of proven light water technology. Much of their materials, fuels and modeling research is dedicated to ensuring the safety of operating reactors and to exploring life extension, instead of advancing non-light water designs, as Figure 2-4 demonstrates. In playing this role, NE has moved close to becoming a service provider for the light water industry. As a consequence, industry lacks the incentive to conduct this research in-house and transfers it to the government in the knowledge that a Congress under pressure from industry support groups will fund it. Perversely, the funder of last resort has become the funder of first resort.

Where NE does support truly innovative research that private industry has mostly ignored, it is prone to changing priorities, terminating programs before they have achieved few if any of their objectives (Figure 2-5). The clearest example is NGNP, where sensitivities to site location, technology choice, and cost share eventually led to effective termination when no commercial partner could be found to continue the effort. Such behavior might appear to be a political asset in the short-term. While termination may have been reasonable given the lack of industry partners, a better partnering construct may have helped save the program. Ultimately, the failure of this type of effort undermines NE's credibility, and reinforces its standing as an office that lacks focus and vision, and cannot deliver on its advanced fission programmatic commitments. The policy ramifications for nuclear energy are stark, given that the mitigation window for decarbonizing the energy sector is, essentially, the next several decades.(30)

An array of earlier studies pointed to some of the challenges facing nuclear innovation in the U.S., though suggestions for improvement consist mainly of appeals to NE to better enable private enterprise's use of its facilities and resources.(20) Our analysis suggests that the problem facing NE is acute enough to warrant a new approach. Because dramatic increases in its funding level are unlikely,(20) it must exercise stricter programmatic discipline. To that end, it is imperative that NE establish a transparent process for evaluating the various advanced reactor concepts it supports across key performance requirements. The goal of this process should be to provide a robust channel for debating the economic, safety, security and waste implications of various designs. An independent panel of experts—perhaps a presidential blue ribbon commission or a

National Academy of Sciences committee—should then identify, in consultation with key stakeholders, the one or two that best meet these key performance requirements. While such a process is common in other industries like aviation,(31) it is foreign to the nuclear industry and NE. If adopted, it would allow NE to focus its limited funding better and would be in harmony with the industry's desire for risk-informed, performance-based guidance from government.

Absent a sense of urgency among NE and its political leaders—one that engenders the funding and focus required to develop and deploy a new nuclear technology—the likelihood that advanced reactors will play a substantial role in the transition to a carbon-free U.S. energy portfolio is exceedingly low. From a broader perspective, this failure means that the U.S. will cede its leadership on nuclear matters to other nations, limiting its ability to exert influence in key areas such as safety and non-proliferation, as well.

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CHAPTER 3

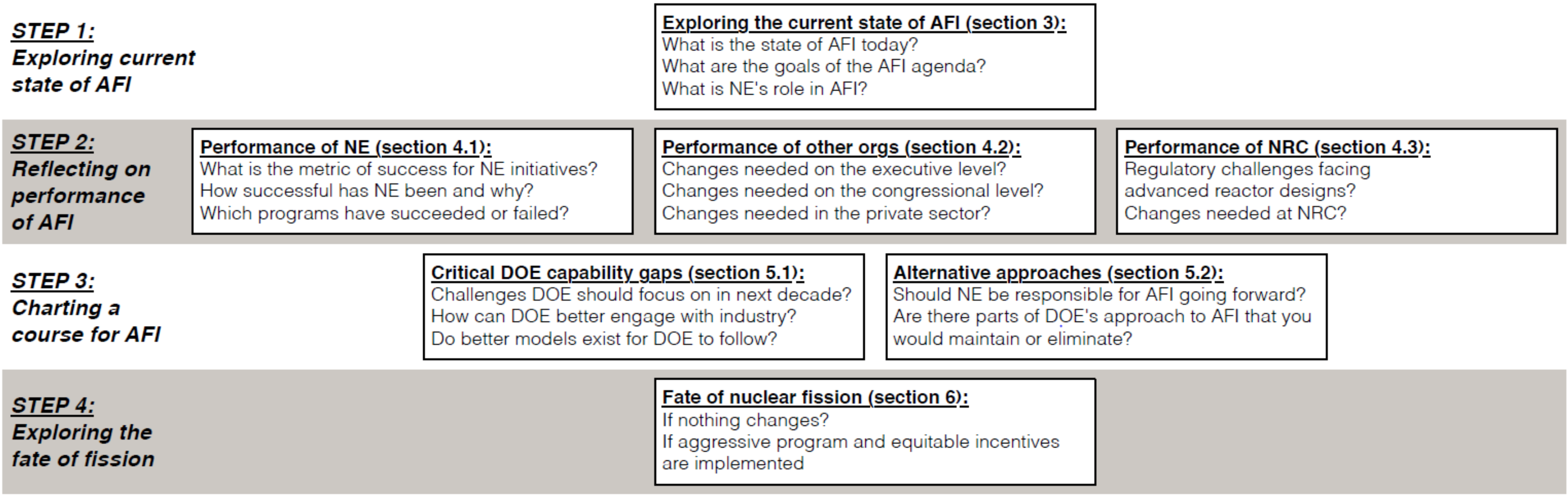
Expert assessments of the state of U.S. advanced fission innovation

1. Introduction

As we discuss in Chapters 1 and 2, deep decarbonization in the U.S. will require a shift to an electrified society dominated by low-carbon generation.(1) Many studies suggest that the most cost-effective way to do this is with a portfolio of technologies that include a role for nuclear power.(1-3) However, the economic and institutional challenges facing large light water reactors (LWRs) make a rapid expansion in the use of current nuclear technologies difficult. For decades, energy planners have envisioned a move to standardized, factory-manufactured systems and non-light water designs, which would alleviate some of the challenges associated with LWRs, including their high cost and concerns about both safety and waste.(4-7) As we describe in Chapter 2, in the U.S., stewardship of this transition rests with the Department of Energy's (DOE) Office of Nuclear Energy (NE), an applied research and development (R&D) office charged with developing and demonstrating advanced reactor technologies.(8) We find in the budget assessment described in Chapter 2 that despite repeated roadmaps indicating a commitment to innovative designs, NE has failed to fulfill this mission, and no advanced reactor design is remotely ready for deployment.It lacks both the funding levels and programmatic focus to execute its non-light water reactor mission.(9) NE's difficulties in fulfilling its role highlight a fundamental challenge to major transitions in the energy system. How can limited government support for emergent energy technologies be allocated judiciously, and specifically, how can NE better enable nuclear innovation? Answering these questions ultimately requires expert judgment. Here, we report results from interviews we conducted with 30 senior nuclear energy veterans from across the enterprise—all with extensive knowledge of NE and the history of nuclear technology development—to elicit their impressions of the state of nuclear innovation in the U.S. and its likely future prospects.

2. Method

We conducted semi-structured interviews with subject matter experts that lasted two hours on average, making this one of the most in-depth assessments of the challenges facing nuclear innovation. Semi-structured interviews were necessary for three reasons. First, metrics of program success are opaque—where they exist at all—and require more than numbers to explain. Second, diagnoses of performance and prescriptions for improvement varied across participants, and thus we could not use the closed-form lists normally found in highly structured elicitations. Indeed, standard elicitation techniques focus on assessment of key variables and elicit probabilistic distribution functions (PDF) around those variables. For this assessment, adopting this standard model would have severely limited the number of questions we could explore: most could not be parsed into the traditional PDF-elicitation framework. Third, some limited structure was necessary to ensure that the questions delivered and content elicited remained consistent across multiple months. The interview protocol engaged the experts in a wide-ranging assessment of the various organizations involved in the nuclear enterprise. It investigated past and current performance, elicited suggestions for improvement, and assessed the likely future prospect for nuclear fission under two distinct scenarios. The protocol was thus broken down into sections, as shown in Figure 3-1.



STEP 1:
Exploring current state of AFI

Exploring the current state of AFI (section 3):
What is the state of AFI today?
What are the goals of the AFI agenda?
What is NE's role in AFI?

STEP 2:
Reflecting on performance of AFI

Performance of NE (section 4.1):
What is the metric of success for NE initiatives?
How successful has NE been and why?
Which programs have succeeded or failed?

Performance of other orgs (section 4.2):
Changes needed on the executive level?
Changes needed on the congressional level?
Changes needed in the private sector?

Performance of NRC (section 4.3):
Regulatory challenges facing advanced reactor designs?
Changes needed at NRC?

STEP 3:
Charting a course for AFI

Critical DOE capability gaps (section 5.1):
Challenges DOE should focus on in next decade?
How can DOE better engage with industry?
Do better models exist for DOE to follow?

Alternative approaches (section 5.2):
Should NE be responsible for AFI going forward?
Are there parts of DOE's approach to AFI that you would maintain or eliminate?

STEP 4:
Exploring the fate of fission

Fate of nuclear fission (section 6):
If nothing changes?
If aggressive program and equitable incentives are implemented

Figure 3-1: Schematic outline of the topics covered in our interviews on the state of advanced fission innovation (AFI) in the U.S. Time runs from top to bottom.

The protocol included the use of both open response queries and a number of basic ranking exercises. Prior to beginning the interviews, we explained the purpose of our study as an "assessment of the state of advanced fission innovation in the United States", taking care to provide no hint of bias. Question design was reviewed carefully to avoid leading or priming. During ranking exercises, participants' rationales for ranking order were elicited only after these rankings were made. Examiners made counter-arguments, where appropriate, to assess the strength of the positions taken by participants. Participants received no prior notice of the nature of the questions, and no compensation was provided. All interviews were conducted by two interviewers at the offices of the participants. One of the interviewers served as primary questioner, while the other severed as primary recorder. Following each session, the primary recorder transcribed notes in electronic form. Both interviewers reviewed and approved the final interview transcript.

Cumulatively, the 30 experts have over 750 years of experience in the U.S. nuclear enterprise, and were drawn from the federal government (both DOE and Congress), the national laboratories, academia and industry. Participants were recruited by first assembling a list of recognized experts in the area of advanced nuclear innovation. This list came from both a literature review and an assessment of national lab, DOE and Congressional staff leadership listings. Requests for participation were then sent to a large group (>50); the requests explained the motivation and duration of the proposed interview. The thirty who accepted include people who designed the reactors, materials and fuels responsible for establishing U.S. technological and industrial leadership in nuclear energy. In order to assure frank discussion, we promised anonymity, given the experts' positions and the sensitivity of the subject matter. This was disclosed as part of a pre-interview informed consent form. The entire protocol is reproduced in the Appendix at the end of this chapter.

3. Step 1: Exploring the current state of advanced fission innovation (AFI)

In our opening section, we asked the experts to reflect on the current state of U.S. AFI, and then to reduce their diagnosis to a few words or phrases. Twelve of thirty gave a vague assessment using terms such as “evolving” and ten were distinctly negative about the state of innovation. Eight provided a description that reflected a current state that was trending in a positive way. Responses were clearly tied to each expert’s frame of reference, with seasoned veterans of the enterprise—active in the 1960s and 1970s—taking a decidedly more negative tone than more recent entrants into the field, who remember only the dearth of activity in the 1980s and 1990s. The majority believes that efforts to innovate have failed to deliver tangible results. Most elements of the enterprise have atrophied, including the available facilities, the commercial nuclear supply chain and the human capital. One expert characterized it as “on the brink of death,” with the vague “evolving,” “nothing new,” “aimless,” “academic,” and “disjointed” five common descriptions.

Among those who provided vague or negative assessments, more than half qualified this by noting that the growing level of interest in AFI is “exciting” or “encouraging”. They deem this a “modest” revival, considering the dearth of activity that existed just a decade ago. The reason for this excitement is the involvement of young entrepreneurs, most of whom are supported by private capital.[1] Even the most optimistic experts conceded that the current level of activity is primarily academic. At best, “all we have is [intellectual property], not actual products”, and it is therefore unclear where this modest revival will lead or what it will accomplish.

To examine the reasoning behind their assessments, we asked participants to explain how the state described had been reached. The universe of explanations was limited enough for us to summarize their responses in Table 3-1 below, which breaks these down into three categories according to the level of optimism exhibited in their short characterizations of the state of AFI. Notably, even those experts who were optimistic about the state of innovation in the field qualified their responses. While they saw reasons for hope, they uniformly acknowledged the sheer scale of the task that lies ahead and all noted that past efforts have failed. As the table shows, their positive assessment was

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[1] Although over thirty new startups exist in the U.S. alone, private funding is dominated by a small number of companies with wealthy backers, such as TerraPower.

based on broader cultural changes that are driving the need to re-examine nuclear power as an alternative.

Table 3-1. Rationales provided by the experts in explaining the state of advanced fission innovation in the U.S.

Reasons for **positive** assessments (8 of 30 experts)	Reasons for **vague** assessments (12 of 30 experts)	Reasons for **negative** assessments (10 of 30 experts)
1) Climate change 2) Need for energy 3) Cultural shift: younger minds with better tools	1) Industry's short-term focus 2) Inefficient R&D apparatus 3) Poor coordination between government & industry	1) Poor economics 2) Limited R&D funding 3) Entrenchment of entrenched industry 4) No strategic energy policy

We next asked each expert three key related questions that set the stage for the rest of the interview: 1) Which entities should lead the AFI enterprise? 2) What should be the goals of AFI in the U.S.? 3) What should be the role of NE within the larger advanced fission enterprise?

Opinions regarding who ought to lead the advanced fission enterprise differed. Responses from 21 of the experts fell on a spectrum that ranged from DOE on one extreme to private industry on the other. The group that endorsed the latter view saw government as a facilitator that ought to provide private vendors with its existing knowledge base, facilities and resources. Skeptical of this notion, the group that endorsed DOE noted the scale of the task at hand, the fickleness and short-term priorities of private enterprise and the wreckage of previous private ventures. Of the nine who fell outside this spectrum, four saw the national laboratories as the repository of AFI knowledge, and thus its natural leaders. Three experts considered research universities the obvious leaders in innovation, while only two trusted the utilities to lead.

There was agreement about the goals that must motivate research, development and deployment activities. The enterprise's goal, and its ultimate measure of success, should be to ***build a demonstration unit***. In order to achieve that goal, the enterprise ought to pay attention to developing the technical and regulatory framework within which one or two new advanced technologies would operate, and make sure that the product fulfills customers' needs.

As for the role of NE, more than two-thirds of the experts declared that they ought to be mainly a facilitator, or enabler, of research. They should conduct research that is high-risk and potentially high-reward, and maintain the facilities that buttress innovation in the industry, as opposed to micro-managing its activities. Because NE has been the steward of public monies dedicated to AFI, we dedicated a section to assessing their past performance.

4. Step 2: Reflecting on past performance in AFI

4.1. The Office of Nuclear Energy

While all organizations involved in the AFI enterprise have hindered innovation according to our experts, by far the greatest amount of criticism was directed at NE and the political establishment. Officially, one of NE's core missions is to support the development and demonstration of advanced, non-light water reactors.(8) Asked to gauge NE's success in this particular mission, the experts delivered a damning verdict, as shown in Figure 3-2.

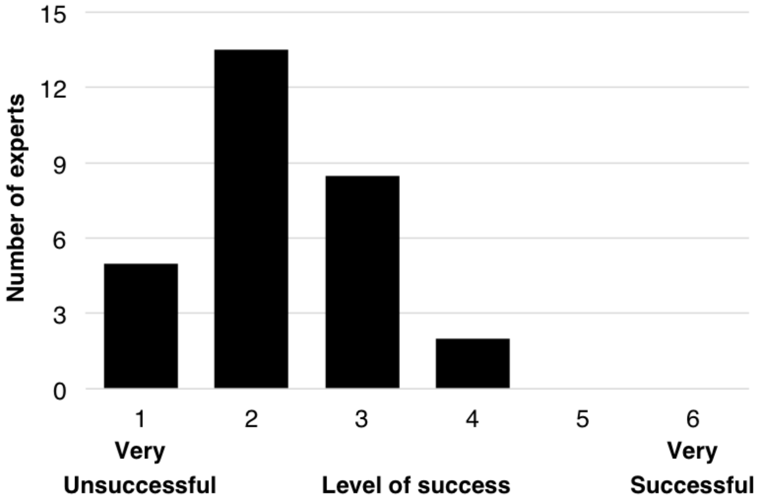


Figure 3-2: Ratings of NE's success in supporting the development and demonstration of advanced, non-light water fission reactors were recorded on a six-point scale, ranging from very unsuccessful (1) to very successful (6).

Part of this discussion was intended to elicit metrics of success with which to gauge NE's programmatic initiatives. As we note in the last section, most experts indicated that the ultimate metric of success was a deliverable "product." A deliverable product is one that sits high enough on the technological readiness level (TRL) for industry to pursue without extensive public support. The discussion was designed to evolve into one that assessed NE's major programmatic initiatives over the past two decades. The experts provided examples of initiatives they considered successes or failures, and there were far more examples of the latter. Seminal programs like the Global Nuclear Energy Partnership (GNEP), which ran from 2007 to 2008, and the Next Generation Nuclear Plant (NGNP), which was intermittently funded from 2005 to 2013, were judged abject failures. The reasons for failure differed in each case. In some cases, NE misjudged when and how to hand-off projects to industry; NGNP is a prime example of this. In others, participants indicated that NE micromanaged its grants to an extent that industry deemed intrusive. Some failures were caused by factors beyond NE's control: for instance, inflexible cost-sharing arrangements mandated by Congress and the Office of Management and Budget (OMB) make it difficult for industry to collaborate with NE. Even when the fault was not entirely its own, NE came in for withering criticism because of its lack of programmatic discipline. It rarely follows through on its advanced, non-light water reactor projects: it does not fund them at the level or duration necessary for project success, and it is overly attuned to political sensitivities, which means it often discards entire programs in favor of others that are more politically palatable. These faults are apparent in the budget analysis of NE we presented in Chapter 2.(9)

The NP2010 program—initiated to complete the design certification and licensing of two LWR designs, one of which is under construction domestically and overseas—was judged a success. Also deemed successful was the Nuclear Energy Plant Optimization (NEPO) program, which improved the performance of the aging fleet of operating reactors. The extensive work done on advanced fuels was considered the only successful component of the NGNP program, though experts pointed out that this is now decoupled from any ongoing reactor development effort. All three succeeded because they lasted long enough to sustain or generate an actual, deployable product. The experts acknowledged a number of current projects that have been touted by NE as examples of its improving performance—such as small modular reactor development and improved modeling and simulation—but most felt that it was too soon to judge these programs a success until they had produced tangible products desired by industry.

We offered the experts a closed list of causal factors that might explain NE's performance. Experts were asked to rank these by importance; we averaged these rankings, with 7 being the most important and 1 the least. Our results point to three factors being most critical: 1) shifting Congressional priorities, 2) shifting Executive priorities, and 3) the lack of consistent focus, vision and leadership within NE. Other factors, such as NE's funding level, the competence of its staff and the public's distaste for nuclear power occupied a distinctly second tier, as shown in Figure 3-3. Most recognized that these factors were interrelated, and argued that the factors in the second tier are surmountable if the top three challenges are resolved. We did offer blank cards for participants to suggest alternative causes for NE's performance, but only one did so, adding "lack of market pull" as a distinct factor.

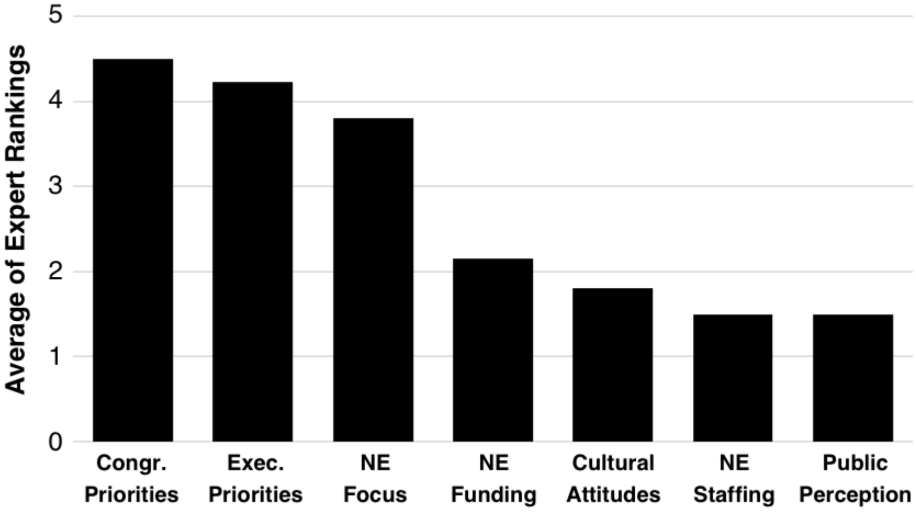


Figure 3-3. Experts ranked the importance of factors that contribute to NE's performance on a scale of 1 to 7. We average their rankings here, such that the taller columns reflect more important factors.

While NE's support of light water technologies has been more successful, experts disagreed as to whether this is an appropriate function—or even a desirable one—for an applied R&D office. While one explicitly argued that evolutionary improvements in light water reactors constitute "innovation," most experts felt that the role of government should be to fund long term, revolutionary projects, as opposed to sustaining and incrementally improving an already well-performing LWR fleet. This view does not differ from what is generally perceived to be the classic role of government in technology innovation, as described by Vannevar Bush in 1945.(10) This classic framework considers it the role of government to lead complex and long-term technology development. While these generate limited immediate payoffs, the role of government is to retire enough of their associated risks and costs before private enterprise capitalizes on their benefits. Under this model, incremental improvements in technology are the domain of private industry.

Instead of restricting its scope to areas where industry lacks the funding or the facilities to innovate, NE is engaged across the entire enterprise, spreading its focus and expenditures over myriad, disparate activities. We countered suggestions of a "lack of focus" by pointing to the large number of road maps and strategy documents published by NE. These were brushed aside by frustrated experts—in some cases, by their authors—with one stating that, "yes, we have enough roadmaps to publish an atlas. And yet, no vision." NE's *real* goal is to maintain its funding stream, "flying under the radar to the greatest extent it can in order to avoid political controversy, and it generally succeeds at that." Asked how NE chooses the projects it funds, experts most familiar with the process deemed it an "old boys' club," where investigators are funded "if NE had funded them in the past." NE favors funding "known quantities" in order to "prevent surprises." Evidence of good performance or innovative research too rarely comes into the equation, and NE is most definitely not interested in "taking risks:" it neither rewards nor encourages radical deviations from its programming norm.

The experts lamented the fact that the U.S. nuclear enterprise finds itself in the unenviable position of being led by an organization that avoids taking risks and making hard decisions, frowns upon ambitious, long-term projects, funds them at a low level and is most concerned with the next appropriations cycle. On the other hand, the most aggressive of the new private entrants do make hard decisions, acknowledge that research takes time, spend large amounts of money on their projects and collaborate closely with nations that have the necessary facilities and a receptive environment for new development. One example that was noted repeatedly is the recent effort by TerraPower to team with major developers worldwide.(11) This constitutes a reversal in the classical roles of government and industry, and points to a risk of pending irrelevance for U.S. R&D, as companies seek partnerships that lie outside its sphere of influence.

Interviewees were also critical of NE's staff. Because NE is judged to lack technical expertise, it is forced to rely on experts from the national laboratories for advice. These experts, in turn, have their own favorite projects to protect. The result is a guaranteed funding stream for existing projects that might not bolster the overall mission. It can also result in infighting among the laboratories, which leads to the development of a number of technologies—"some of which should not be pursued"—and a further dilution of NE's overall focus. Rather than lead them, NE is instead captive to the laboratory experts it funds.

Another oft-repeated criticism of NE is its disengagement from industry. For example, the failure of NGNP was attributed to NE's decision to locate the project in Idaho, away from potential industry customers. According to participants, the disadvantages of choosing this location vastly outweighed the advantages. Moreover, NE's collaboration with industry on this project was fundamentally flawed, from the selection of the technology, to Congress and OMB's insistence on a 50:50 cost-share from the beginning, and the unresolved question of intellectual property ownership once the technology is commercialized. According to one expert, "if a company wants to build NGNP, it could. No one wants it. DuPont is not going to build the first-of-a-kind plant when their competitors get to build the second one for half the cost."

A follow up discussion on cost share and funding mechanisms indicated general support for the concept of shared responsibility, with eighteen of thirty experts indicating support for some version of the current cost-share mechanism. However, all suggested that tailoring was required to prevent NGNP-like failures in the future. Suggestions ranged from a nuanced cost sharing mechanism that scales to a technology's position on the TRL, to a more dramatic change in the nature of government support, such as a "Space-X" competition that would encourage industry to compete for a large prize.

Finally, in examining the many executive-branch pressures that NE is subject to, the Office of Management and Budget was noted as an obstacle, despite its essential role. The most repeated criticism of OMB related to the negative impact of its short-term budget focus, and how it runs counter to the long-term R&D funding commitments that groundbreaking energy (and other) research demands. As noted above, the experts indicated that the most successful programs were those that had consistent budgets over time.

4.2 Industry and the wider federal government apparatus

Although we dedicate a section to NE, there was also ample criticism directed at other organizations. The experts delivered withering attacks on the dysfunction in both the executive and legislative branches of government. The low scientific literacy of Congress, the distortive effects of the budget cycle on program continuity and the general emphasis on short-term tactical gains as opposed to long-term strategic calculation were noted universally. Experts uniformly criticized the ***lack of a national, strategic energy policy*** in the U.S.

The broader DOE bureaucracy was also criticized for its lack of focus and strategic thinking. Some noted how, despite being responsible for nuclear innovation, DOE's other offices and arms sometimes disfavor nuclear, "undermining our ability to meet climate goals". The sheer size of DOE's mandate emerged as a problem. One expert lamented, "we do not have a Department of Energy in this country. DOE is the Department of science, environmental cleanup and nuclear weapons." They questioned the ability of one agency to manage such a diverse portfolio while remaining the steward of energy innovation.

Industry also received significant criticism, including from experts affiliated with it. Most lamented the lack of private R&D, a capability that has to a large extent "atrophied." Several experts went on to state, "we don't have vendors anymore." While industry eagerly accepts DOE research dollars, it tends to spend them on work it would have undertaken anyway.   Much of this criticism was directed at the established nuclear technology vendors that have historically built and maintained the existing fleet. The alternative model most recommended is that of the recent startups whose backers, recognizing the need for energy breakthroughs, have unexpectedly proven to be sources of "patient capital." The focus on short-term profits by both established vendors and utilities destroys the desire and capacity to foster capital-intensive projects. There was palpable anxiety about poor decision-making on the part of private enterprise, which, when applied to a sector like energy, begets strategic risk.

4.3. The Nuclear Regulatory Commission

The complexity and cost of nuclear regulation has frequently been noted as a factor that stymies nuclear innovation.(2) Given this, we expected the experts to be critical of the Nuclear Regulatory Commission (NRC), and some were. In general, however, the Commission emerged as a competent executor of its mandate, with many of its shortcomings due to factors beyond its control. There are two major problems with the NRC, according to interviewees. First, it is a light water regulator, with little to no current technical competence in regulating advanced reactors. But this is the entirely predictable result of how it is structured: since the mid-1990s, more than 90% of the Commission's budget has come from fees paid by plant operators. It is hard to justify expending tens of millions of dollars on establishing non-light water regulations to utilities (with active lobbying groups) that exclusively operate LWRs.

Second, the Commission is criticized for having a prescriptive, rule-based approach to regulation. Since these regulations are crafted with LWRs in mind, advanced reactors that circumvent light water's challenges—for example, designs that do not require expensive containment structures—are automatically disadvantaged. In the past, some have suggested that the Commission move to a risk-informed, performance-based regulatory framework. While the Commission's most recent roadmap embraces this,(12) the experts criticized people who "parrot this line" at every meeting without "telling the NRC what they mean by it" or how it should be implemented.

5. Step 3: Charting a course for AFI

5.1. Critical DOE Capability Gaps

We asked the experts to list the challenges facing AFI in the U.S. in the next ten years. Three issues emerged as most critical. First is the ***diminished state of the technical infrastructure***. Most saw a clear need for improved facilities—chief among these a fast flux testing capability in order to qualify new fuels and materials. Currently, most of this testing is being done in Russia, in a facility that will soon be decommissioned. A new

French reactor may provide some needed near-term capability. The experts, including several from the national laboratories, noted reluctance to explore the consolidation of facilities across DOE because of the political sensitivity of this process. In their judgment, consolidating facilities would free up funding for new infrastructure that might accelerate innovation and maintain U.S. technical leadership.

The second challenge is ***developing the standards and regulatory guidance that would enable a predictable licensing regime***. This factor emerged as critical among experts who belonged to new startup companies. While they believe that their private capital is patient, it is not infinitely so: a staged regulatory process is needed to provide regular feedback to investors, as they consider additional investment. We note that efforts to address this issue and to also enhance advanced reactor development have been underway for the last two years. In January, the U.S. House of Representatives introduced H.R.590, the Advanced Nuclear Technology Development Act of 2017, which directs DOE and NRC to enter into a memorandum of understanding that ensures that: 1) technical expertise at DOE and NRC that supports private sector development of innovative reactor technology is maintained; 2) modeling and simulation is utilized; and 3) DOE facilities are available to the NRC as needed. In addition, the NRC is required to report to Congress on existing federal activities that relate to testing and demonstrating advanced reactors with significant design improvements over existing commercial reactors and plan for establishing a framework for licensing such reactors. Finally, the bill authorizes appropriations to the NRC that would help it to develop a regulatory infrastructure for advanced nuclear reactor technologies outside the current statutory fee recovery requirements.(13) If these efforts are funded, they may address some expert concerns.

Third is the ***lack of evidence-based market signals*** that would value the benefits of low-emission nuclear power, just as it would other capital-intensive, low-carbon technologies such as carbon capture and sequestration.(14) While there was broad consensus that these challenges are critical to address for substantial progress to be made, none was deemed insurmountable in the presence of strong leadership.

5.2. Alternative Approaches

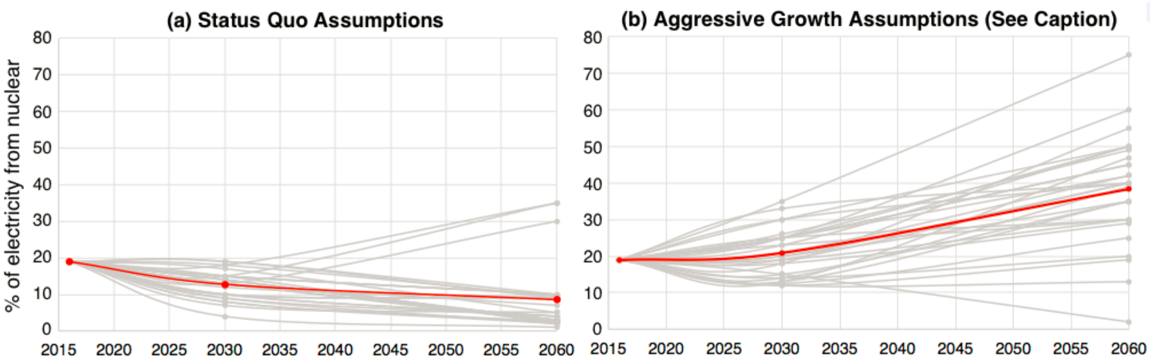
The experts disagreed about how the U.S. ought to move forward. Four suggested that the national laboratories, where most government expertise lies, should lead. Ironically, this argument was not articulated by leaders within the laboratory system, despite the considerable patronage such a move would entail. Five suggested that universities should assume a greater leadership role, both in advancing basic research and in conducting social scientific analyses of nuclear power's sustainability. Seven suggested that NE, despite its problems, ought to lead the effort outright, while more than half believed that it should be a partnership between NE and industry. Most suggested that NE could still be salvaged if the political leadership prioritizes its mission, and if industry is supportive. Paralleling Winston Churchill's comments about democracy,(15) NE was judged to be the worst steward of the nuclear enterprise—except for all the others.

Given their assessment that NE was still the most likely government lead, we asked our experts what changes are needed to enhance its effectiveness, and there was consensus on the following three. First, ***NE's mission needs to be restated***: to develop and deploy one or two non-light water reactor designs that could be scaled up when the inevitable need for deep cuts in greenhouse gas emissions is embraced by the nation's leadership. NE needs to focus on applications—it is not a basic science agency. Given nuclear power's high cost, it should restrict itself to a few development projects with the ultimate goal of ***building advanced operating prototypes***. Second, instead of maintaining infrastructure that is a legacy of the weapons program, NE should ***consolidate its facilities***. This would involve both abandoning decades-old infrastructure and building new test facilities. Third, it should ***develop rigorous, peer-reviewed performance standards*** for project selection and execution, and involve industry and academia as it prosecutes its mission.

6. Step 4: Exploring the fate of nuclear fission

In the final section of our interviews, we asked the experts to consider the future of nuclear fission, and to estimate the likely contribution of nuclear generation—both light water and advanced—to the U.S. electricity system in the near and medium-term.

Twenty-seven out of thirty experts believed that, absent a dramatic improvement in focus and political support, the chances that the U.S. will develop a viable non-light water design in time to make a difference in carbon mitigation are low. Even with greater focus, the future viability of nuclear power in general is uncertain, given how energy markets inherently disfavor it. When asked to forecast the percentage of electricity that nuclear power will generate in the near (2030) and medium (2060) terms—under *status quo* assumptions—the experts drew curves that showed a gradual decline in generation, with nuclear power confined to the regulated markets of the southeastern U.S. Three outliers could not imagine that the U.S. would continue to ignore nuclear in its response to climate change, and predicted a bright future instead. In Figure 3-4a, we outline their responses.


(a) Status Quo Assumptions

(b) Aggressive Growth Assumptions (See Caption)

Figure 3-4: (a) Expert assessments of the percentage of U.S. electricity generation that will come from nuclear power through the year 2060, assuming "status quo" R&D efforts and no dramatic changes in climate policy. **(b)** Experts are more optimistic about nuclear power's contribution to the electricity mix if an aggressive advanced fission R&D effort is undertaken, NRC advanced reactor licensing is streamlined, and the U.S. becomes committed to a low-carbon future by the year 2020. Red lines reflect the average of expert assessments.

We repeated this exercise under the following three assumptions: first, that an aggressive advanced nuclear R&D effort is organized to deploy non-light water reactors; second, that the NRC develops a regulatory process for these; and third, the U.S. commits to a low-carbon future by 2020. There was *very* wide variability in the responses, shown in Figure 3-4b, with the range of potential outcomes spanning everything from the technology's demise to its clear dominance. Even under our aggressive scenario, the majority did not envision widespread commercial development of an advanced reactor in the U.S. until after mid-century, beyond the point when significant carbon reduction must be well underway. Any significant growth in nuclear power—until the latter part of the century—was attributed to further deployment of advanced light water designs. As noted in section 3, experts' frames of reference affected their perspectives. The outer boundaries of the responses to this aggressive growth scenario were set by industry experts, with representatives from the more established companies indicating significant skepticism about future prospects of the enterprise, whereas the new generation of entrepreneurs were very optimistic.

Asked to identify the one challenge facing nuclear fission that they most want to see resolved, waste (10/30), public perception (9/30) and the economics of nuclear power (7/30) figured prominently. Experts noted that these have little to do with advanced fission innovation, and that they would hold sway in any discussions of future use of nuclear power in the U.S.

7. Conclusions and Policy Implications

Determining the level of government support needed for technology transitions is always challenging, given limited budgets and competing priorities. This is perhaps more difficult in a nuclear enterprise that has had a long history of government leadership, not just in basic research but also in reactor development and deployment. While most experts delivered a consistent diagnosis of the problems afflicting the enterprise, there was limited consensus on path and prospects for success moving forward. From a policy perspective, the implications are stark. Even with aggressive assumptions, experts indicate that advanced nuclear is unlikely to play a role in the timeframe necessary to deeply decarbonize the energy system and avert the worst consequences of climate change.(16)

To address this challenge, a fairly consistent list of goals emerged. Experts saw a need to clarify NE's overarching mission for the coming decades: support for the development and construction of advanced fission prototypes. In their view, NE should be an applied R&D office and neither a basic research agency nor the research arm of the light-water industry. Once that understanding permeates, experts elaborated two additional actions.

First is the need to consolidate existing infrastructure: the extensive, aging facilities that currently exist are of limited utility for advanced nuclear development. Experts recognize that this will face significant political opposition, much like that faced by the U.S. Defense Department with Base Realignment and Closure (BRAC).(17) Research in advanced fission is spread across multiple national labs and universities. Consolidation that would free up the funding to develop the demonstration and test facilities the experts believe are needed might be extremely challenging.

Second, given the limited technical expertise within NE and the wide range of stakeholders vying for its appropriations, rigorous peer-review standards must be adopted to ensure each of NE's projects contributes to meeting its goal of supporting the development of advanced fission prototypes. Our experts indicate that NE is still an appropriate facilitator of these goals, but suggest including outside agencies such as the National Science Foundation in developing these standards and assessing progress. Achieving these goals will require a coordinated effort and, while some still saw NE as the likely choice to lead, many felt that a new leadership approach was required given past dysfunction. As noted earlier, a number of experts recommended a significant change in the structure and mission of NE, advising that they move to a supporting role, enabling private sector innovation by making technical infrastructure and laboratory expertise more readily available. When coupled with a revised NRC regulatory approach, they felt this was a more prudent path that would avoid placing government in the position of driving or limiting market choice. This option has the advantage of being driven by the newest and most active of advanced reactor developers, who are trying to improve the prospects of nuclear energy in the U.S., and whose views are the most optimistic of those reported in Figure 3-4.

Many of the more senior experts, who had lived through multiple reorganizations of the DOE NE organization, felt a more radical change in structure was needed. While they recognized that NE might still play a role, they believe overall leadership and oversight should come from a new, independent organization. This structure would be similar to the one spelled out by a recent Secretary of Energy Advisory Board Report (SEAB),(18) which envisions a quasi-public corporation that would lead the effort, beginning by re-focusing funding on a small number of advanced reactor initiatives. According to the SEAB report, this approach would first require a robust and transparent effort to down-select to just one or two promising technologies. NE would be intimately involved in the process, but in a shift from past efforts, an independent panel of stakeholders with strong political backing would lead the overall effort. According to the experts who supported this option, the benefits of such a process would be apparent to any who examine NE's "unfocused and unsuccessful" past funding for advanced reactor initiatives. While dedicated funding for fuels development and light water reactor sustainability have yielded successful products, advanced reactor funding patterns—spread over multiple technologies—have hampered development efforts over the past twenty years.

The diversity of our expert pool may explain why there was little consensus on the appropriate path forward. In addition there are inherent limitations to developing future research agendas when interviewing experts so intimately exposed to the existing paradigm. Indeed, their prescriptions might reproduce some of the failures of the present system. Even an aggressive effort to fix NE might still relegate the U.S. advanced reactor program to fragmentation, vicissitudes of political priorities, and chronic under-funding. Other strategies might look far beyond the NE model, although these attracted less attention from our experts in this analysis. Examples might include a system of deployment prizes that could incent private funding—a topic raised by just one of our experts. Instituting more credible routes to deployment by reforming the NRC might amplify the ability to raise private innovation funding. Another approach, suggested by several experts, is to collaborate internationally with other large, innovating countries that could offer viable routes to market—perhaps notably with China. The challenges associated with export control and intellectual property remain large and unresolved, as several private developers testified. While the task of evaluating this wide range of potential strategies lies beyond the scope of this paper, it is important to acknowledge that only a subset of the universe of policy alternatives was considered, given the limitations inherent in our experts' frames of reference.

Regardless of strategy, achieving these revised goals, either under a status quo leadership structure or one of the new approaches described by the experts, will require political support. Participants said that a coherent national energy policy would be welcome and it is apparent that a key component of this policy must address NE's leadership shortfalls in a way that will allays experts' concerns. Absent such a vision, the only realistic alternative is for the range of energy policies that exist at the federal, state and local levels to clearly recognize the benefits of nuclear energy and provide market prescriptions that reward nuclear power for its low-carbon generation. The responses we received suggest that, should the enterprise proceed along its current trajectory—with limited political support, unfocused funding, stagnant leadership, and aging infrastructure that is of limited utility—the most likely outcome is a slow demise of both nuclear power and nuclear R&D in the U.S., and the nation’s gradual shift from a position of leadership on nuclear matters to the periphery. The consequences of this diminution will extend to the security arena, reducing its ability to craft and maintain international norms. Strategic vision and focused leadership are needed if a shift in trajectory is to occur.

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Chapter 3 - Appendix A – Interview Protocol

Charting a Course for Innovation in U.S. Nuclear Fission Research

Thank you again for agreeing to participate in this interview. We are conducting interviews with experts from government, industry, academia, and nongovernmental organizations regarding the course of innovation in U.S. fission research. We plan to use what we learn to supplement the empirical research and modeling that our group is already undertaking in an effort to chart the course for future research in this space.

First, I'd like to take you through our consent form. (Review form and obtain signatures – ensure a copy is provided to each participant).

Next, while some of this was covered on the consent form, I’d like to give you a brief overview of our research purpose and process. We will start this interview with several open-ended questions. Then we will move on to a series of more focused questions about the history, present, and future of advanced nuclear fission research and development.

(If required) As indicated on the consent form, our study will examine past and current RD&D funding for the Department of Energy, focusing primarily in the Office of Nuclear Energy and the National Laboratories, with the objective of assessing the fruits of the substantial research and development dollars that have been expended. We are primarily interested in understanding which programs are supporting the development of advanced reactors in the United States. In conjunction with this budget and process review, we will also ask questions about the state of U.S. nuclear energy innovation and its probable future trajectory.

Ultimately, we are trying to understand where the critical challenges lie, how to overcome them, and what the future of nuclear power in the United States will look like under various scenarios.

Please do not hesitate to ask for clarification if a question is unclear.

If a question is either outside your area of expertise or is in an area that is outside your comfort zone, please let us know and we will move on.

As indicated in the consent form, the information obtained today will not be tied to you directly by name, but rather will be attributed in a “group” fashion (i.e. government, academia, etc...).

Definitions (Use as needed):

From the National Science Foundation:

Basic research is defined as systematic study directed toward fuller knowledge or understanding of the fundamental aspects of phenomena and of observable facts without specific applications towards processes or products in mind.

Applied research is defined as systematic study to gain knowledge or understanding necessary to determine the means by which a recognized and specific need may be met.

Development is defined as systematic applications of knowledge or understanding directed toward the production of useful materials, devices, and systems or methods, including design, development and improvement of prototypes and new processes to meet specific requirements.

Interviewee #_______________

Setting the scene	History of nuclear R&D	Capability gaps	Exploring role of NRC	Critical next R&D steps	Revitalizing DOE	Future of fission
■						

1. Setting the scene: open response questions

1.1) Please describe the **state of U.S. nuclear energy innovation** in a few words. *(Emphasize that this is an America-centric discussion.)*

1.2) In decreasing order of importance, please list for me the three to five **factors that most contribute** to the state of affairs that you just outlined. If you want to first write them on these file cards and then sort them in order that would be fine.

1.3) In decreasing order of importance, please list for me the three to five **entities that are most responsible** for innovating in nuclear fission research. Again, if you want to first write them on these file cards and then sort them in order that would be fine.

1.4) In order to firmly ground the rest of the discussion please outline what you think **should be the goals** of the U.S. nuclear fission research agenda. *(Public and private.)*

1.5) Given these goals, what **should be the role** of the Department of Energy's Office of Nuclear Energy?

Setting the scene	History of nuclear R&D	Capability gaps	Exploring role of NRC	Critical next R&D steps	Revitalizing DOE	Future of fission
■	■					

2. Reflecting on the history of nuclear fission R&D

2.1) To the extent that a goal of the Department of Energy's Office of Nuclear Energy (ONE) has been to **support the future development of advanced, non-light water fission reactors**, how successful to you believe they have been?

Very unsuccessful **Very successful**

☐ ☐ ☐ ☐ ☐ ☐

2.2) I've prepared a number of cards that list factors that may have shaped the ONE's performance in incentivizing the development of advanced fission reactors over the course of the past 40 years. I've also included some blank cards for you to use if you think I've left out some key factors, or you want to focus things a bit more. Please sort these cards in the order of the importance you believe they have played.

Institutional considerations:

Funding

Focus

Staffing

Socio-political considerations:

Immediate public attitudes

Congressional priorities

Executive branch priorities

Broader cultural attitudes

Others:

2.3) Based on your experience and impressions, please elaborate on the **process** that the Office of Nuclear Energy follows when it **chooses** specific research and development programs for **funding.** How are research priorities determined?

2.4) How would you define success for a Department of Energy Office of Nuclear Energy R&D initiative?

2.5) To the extent you can, please suggest one Office of Nuclear Energy program in the past 20 years to further advanced fission reactors that you would consider a **success**? What factors contributed to making it a success?

2.6) To the extent you can, please suggest one Office of Nuclear Energy program in the past 20 years to further advanced fission reactors that you would consider a **failure**? What factors contributed to making it a failure?

2.7) Cost sharing has been used for programs such as the SMR development effort. This approach has been advocated and criticized in equal measure. **What has been the impact of this funding method** and is it being applied correctly based on the level of research involved?

2.8) What **methods** of funding should be emphasized? Should an alternative to cost sharing be devised?

2.9) Based on your experience and impressions, to what extent has OMB guidance impacted R&D expenditure?

2.10) Based on your experience and impressions, please elaborate on the **roadblocks** that would stand in the way of the Office of Nuclear Energy today, if it were given the task of revitalizing U.S. nuclear fission research

Setting the scene	History of nuclear R&D	Capability gaps	Exploring role of NRC	Critical next R&D steps	Revitalizing DOE	Future of fission
■	■	■				

3. Required changes in policy and focus for nuclear fission research

3.1) What, if any, **changes** should be made at the **executive level** (EOPOTUS) if newly dispensed research dollars are to effectively achieve the overarching goal of a revitalized nuclear fission research agenda?

3.2) What **changes** should be made at the **legislative level** for newly dispensed research dollars to effectively achieve the overarching goal of a revitalized nuclear fission research agenda? *(If they ask for an example, suggest incentive schemes in a broad sense.)*

3.3) What **changes** should be made in the **private sector** (VENDORS) for newly dispensed research dollars to effectively achieve the overarching goal of a revitalized nuclear fission research agenda?

Setting the scene	History of nuclear R&D	Capability gaps	Exploring role of NRC	Critical next R&D steps	Revitalizing DOE	Future of fission
■	■	■	■			

4. Assessing the role of the Nuclear Regulatory Commission

4.1) Some vendors who seek to develop and demonstrate advanced fission reactors criticize the Nuclear Regulatory Commission as a light water agency. What **regulatory challenges** do advanced fission reactors face in the current environment?

4.2) Thanks – which of the challenges you mention is the most critical to address if advanced fission is to become a reality?

Setting the scene	History of nuclear R&D	Capability gaps	Exploring role of NRC	Critical next R&D steps	Revitalizing DOE	Future of fission
■	■	■	■	■		

5. Exploring the role of the Department of Energy in advancing nuclear fission R&D in the near future (10 years)

5.1) Which **challenges** facing nuclear fission research should the U.S. government R&D apparatus **focus on in the next decade**?

5.2) (For DOE representative interviews) What **triggers the completion** of Department of Energy funded research initiatives? Do **performance standards** (i.e. annual funding expenditure levels, technology readiness level goals, etc.) exist for R&D projects undertaken under the auspices of the DOE? If not, should a performance standards framework be adopted? If so, what would **this framework look like**?

5.3) Should government be involved in ensuring that new technologies are able to **cross "the valley of death"** (fuel certification and prototyping)? Or should government support cease at a certain technology readiness level?

6. Revitalizing the Department of Energy, the institution most responsible for nuclear fission research

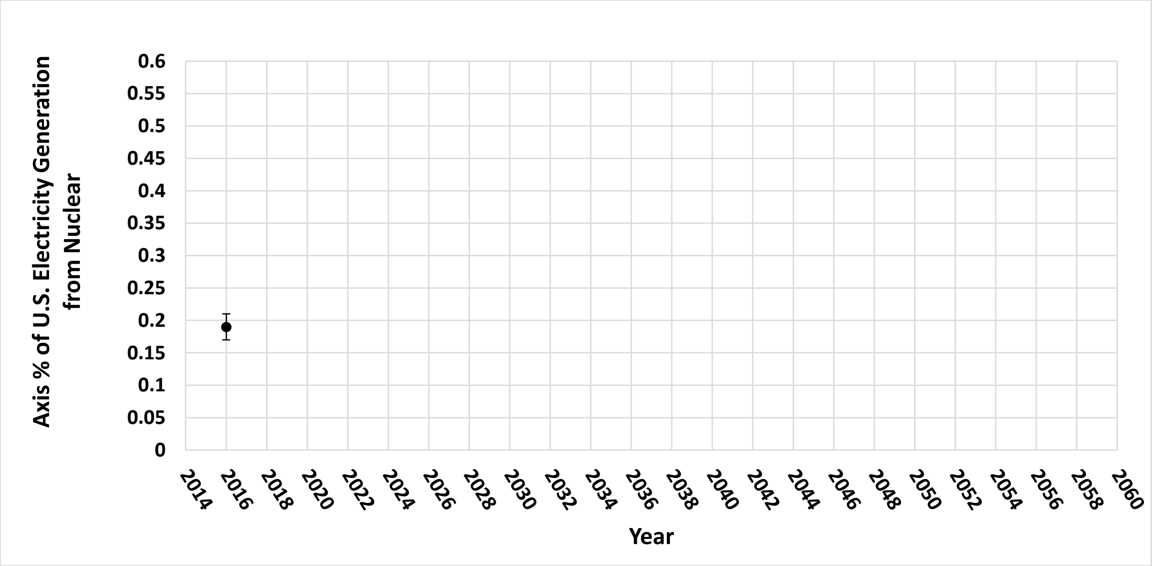
6.1) Should the Department of Energy be the institution that is responsible for advanced fission research going forward? If no, what alternative institutional arrangement might be better?

6.2) Which, if any, **elements** of the Department of Energy's approach to initiating, maintaining, and reviewing advanced fission research and development ought to be **eliminated**.

6.3) Which **elements** of the Department of Energy's approach to initiating, maintaining, and reviewing advanced fission research and development ought to be **maintained**.

7. What is the most probable future for nuclear fission in the U.S.?

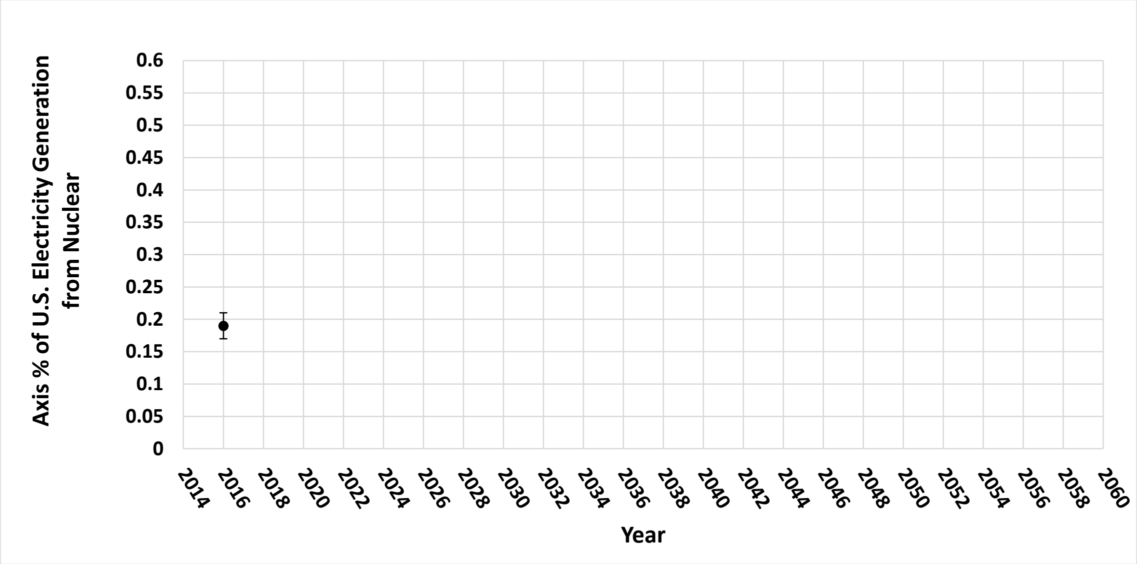
7.1) Today light water reactors produce just under 20% of electric power in the United States. If there are no fundamental policy changes from those that exist at present, please indicate with an X in the plot below you best estimate of what you think that percentage might be in 2030 and 2060. Add a vertical line to indicate your 90% confidence interval.



Please outline the thinking that lead you to make these estimates.

7.2) Now, assume 1) that the most aggressive optimal programs to develop and field advanced designs were started next year; 2) that major changes were made to streamline licensing procedures; and 3) that by 2020 the U.S. had become firmly committed to a low carbon energy future in order to address climate change.

Under that scenario, how, if at all, would your estimates change for what the percentage of nuclear energy might be in 2030 and 2060?



Please outline the thinking that lead you to make these estimates.

7.3) Speaking to issues broader than just the U.S. nuclear fission research agenda, please list and rank the **top five challenges** facing new nuclear power in the U.S.

7.4) Which factors are most responsible for this **likely future** you predict? If you could **remove one challenge** from the list of challenges facing nuclear fission, which would you choose, and why?

Thanks very much for your help with this study.

Follow Up Questions:

CHAPTER 4

The role of institutions in the assessment of global nuclear deployment readiness

Foreword

In our last two chapters, we explored the potential of advanced nuclear designs to fill the future need for low carbon generation. Our findings indicate that a rapid move to new technologies is very unlikely. It is possible, however, that broader use of existing light water nuclear generating technology may still offer some opportunity for addressing decarbonization of the electricity sector worldwide, including to nations that are not currently part of the nuclear cohort. . Nuclear development is a complex undertaking and expanded deployment carries with it more challenges than an increase in renewable or conventional generating technologies. Some of these challenges include controlling the cost of project development, managing security, guarding nuclear materials, developing proficient human capital, and planning for accident mitigation. Before expanding deployment to non-nuclear nations, the current international nuclear control regime gives significant consideration not only to energy need and affordability but also to institutional readiness and political stability, which can be key determinants of project viability. Few systematic, rigorous analyses of the impact of institutions on nuclear deployment have been attempted, and in-depth studies are only conducted for nations embarking on a program. Here we examine nation-state readiness for nuclear development through a benchmarking analysis that incorporates factors reflecting energy needs, economic potential, and institutional readiness. We determine both the impact of institutions on a country's readiness for nuclear power and the upper bound of the market for deploying small modular reactors (SMR), which have outputs of less than 300MW$_e$.

Gigawatt-scale nuclear power projects have fared poorly in meeting cost targets and construction schedules, and are unsuitable for nations with smaller electric grids. It is hoped that SMRs will rely to some extent on factory manufacturing methods that may shorten development and deployment timelines, and perhaps improve cost control. Before SMRs can be built in the quantities needed to contribute to power sector decarbonization, however, vendors must develop the manufacturing pipeline for these designs and, to do that, they must estimate the potential market size and financial risk for the technology. Developers, policymakers, and regulators must also be able to rely on broad measures outlining the risk of development in non-nuclear nations, especially in terms of institutional readiness. Our benchmarking analysis indicates that, while there is a large potential SMR market when considering only need and affordability, incorporating governance and institutional risk factors substantially shrinks the potential size of this market. Our analysis also points to multiple paths for development, some of which may require greater international oversight. If they are to acquire SMRs some less-prepared countries will need to be supported by existing nuclear nations. This is unlikely to happen without strong economic motivation to capture a nascent market. Such motivation is lacking in countries without aggressive, coherent industrial policies. While far more elaborate in-country assessments would be necessary before initiating a SMR power plant project, or before relying on this technology as a path for deep decarbonization, our results highlight where countries stand regarding their readiness for SMR deployment, not to mention how they might enhance that readiness. Our results can also assist vendors, policymakers, and both national and international regulatory bodies in evaluating future development potential and long-term project risk.

1. Introduction.

As we have indicated throughout, a substantial amount of greenhouse gas emissions mitigation will be required is the world is to avoid the most dramatic climate change scenarios outlined in the 2014 IPCC Synthesis Report.(1) Prior analyses have examined the potential for nuclear energy to play a role in decarbonizing the energy sector. (2) Our prior sections lead us to the conclusion that advanced, non-light water reactors are unlikely to be available for large scale deployment until mid-century,(3,4) so existing light water designs will have to continue to play a large role if nuclear power is to remain one of the technologies available to meet carbon reduction goals. But large light water development projects have a history of extended construction timelines, re-work delays, and significant capital risk. Recent reports indicate that of the approximately 55 reactors now under construction worldwide, 35 are behind schedule and many are over-budget.(5) With few exceptions, large-scale nuclear projects have demonstrated neither affordability nor economic competitiveness. Nor are they well suited to nations with smaller energy grids, or to replace fossil generation in the industrial process heat sector.

An alternative to large LWR plants are small modular reactors (SMR), which are defined as reactors with outputs less than 300 MW_e.(6) In theory, these plants could be built in factories or shipyards, improving cost and duration control, and, when needed, could be combined to provide large-scale generation at single locations (e.g. the U.S.-developed NuScale stipulates the deployment of 12 45MW_e reactors on a single site). Some designs may also lend themselves to more flexible deployment options, such as floating power plants. However, before any nuclear vendor takes on the task of developing the manufacturing infrastructure needed to build SMRs, they need an understanding of the potential market size and development risk of this technology. This requires not just an assessment of the number of reactors required to meet demand, but also an understanding of how that market's viability might change if political and institutional risks are considered. Moreover, regulators and international oversight agencies need to understand the implications of broader deployment on fuel cycle security and proliferation risk.

In this analysis, we use a benchmarking technique – Data Envelopment Analysis (DEA) – to examine need and relative readiness for new or expanded nuclear deployment across 175 countries. Our analysis incorporates key factors that affect deployment potential, including institutional factors. We also evaluate our method's sensitivity to different indicators and compare the results to alternative linear modeling techniques. We first evaluate the SMR market size based solely on the world's need for deep decarbonization in the electricity generating sector. We develop two scenarios of deep decarbonization. The first involves a range of grid mixes, incorporating up to a 50% nuclear share. The second involves SMR deployments needed to achieve an 80% reduction in emissions. We determine both the market size and carbon mitigation potential of SMRs when considering needs and economic capacity. We then add institutional factors to the analysis in order to determine how this market size changes. Of course some countries with larger grids might not choose SMRs so we evaluate the size of the SMR market if countries large enough to develop Gigawatt-scale plants choose those preferentially over SMRs. We also identify those assessment factors that have the greatest impact in determining readiness for sustainable nuclear development and compare our DEA results to a simple linear model using the same variables. In an additional scenario, we calculate the same parameters assuming a build-own-operate-return (BOOR) model for the deployment of floating SMR power plants.

Four major categories of variables were chosen to conduct our assessment. Three involve factors from the technical evaluation categories that are recommended by the International Atomic Energy Agency (IAEA) for sustainable nuclear development.(7) These are: 1) economic viability; 2) need for energy generation and nuclear-specific factors including plant size; and 3) environmental factors. We add a fourth category, institutional readiness, to assess the readiness of governance structures across nations, as these account for some of the risk associated with any widespread use of nuclear technology. As noted in a recent analysis of carbon mitigation investments, institutional factors can have a significant impact on investment decisions and may limit the potential for nuclear development in currently non-nuclear nations. (8) The factors chosen for our analysis are described in Table 4-1. We conduct an elaborate sensitivity analysis to ensure the power of our analysis in justifying country performance scores.

2. Background and Literature Review.

2.1. Readiness for energy development. Multiple studies have examined national readiness for nuclear development and explored decision criteria for plant siting. A 2011 study(9) examined capacities and motivations for nuclear development, primarily considering Gigawatt-scale development and the future energy need of developing nations. A 2015 study evaluated national readiness for SMR development using the Analytic Hierarchy Process. (10) Both studies found a considerable number of nations that were well suited for new development. The U.S. Department of Commerce and Brookhaven. National Lab have also developed qualitative readiness metrics to evaluate the readiness of developing countries to deploy nuclear power plants. (11,12) Of the studies that ranked nations according to their readiness for nuclear development, many used initial screening criteria that eliminated a significant number of countries from consideration. Most commonly, this was done based on grid capacity or economic factors (affordability). We note that in some cases, nuclear development has proceeded despite a small grid (Armenia) or a small Gross Domestic Product (GDP) (e.g. Armenia and Slovenia), though these nations were under the Soviet umbrella when this development occurred. Based on this, we begin our analysis begins with only one screen – data completeness – in order to include as many nations as possible in the analysis. We evaluate whether nations meet grid capacity or fossil need limits in a later scenario when deciding whether a country can accept a Gigawatt-scale plant. Only 40 of 215 nations and territories under consideration were removed based on our data availability screen. We believe that the inclusion of as many nations as possible at the initial stages of the assessment is important since including smaller nations in the assessment may yield examples of nations that are viable candidates for nuclear development but perhaps with a different deployment model.[2]

2.2. Economics and the impact of institutions on development. Factors chosen to assess affordability examine a nation’s potential to execute large-scale energy projects,

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[2] Later in summarizing results the number was further reduced to 125 nations, reflecting those nations that have current fossil need that could accommodate the development of a 100MWe SMR.

including their ability to support the capital expenditure and risk inherent in nuclear development. Sovereign credit risk ratings are a typical measure for assessing relative economic readiness across nations and have a demonstrable impact on capital inflows in emerging markets.(13) Credit risk and sovereign risk ratings are also influenced by institutional readiness and can affect the availability of capital to developing nations. As Iyer, et.al have noted, this influences the ability of developing nations to mitigate CO_2 emissions and would certainly impact potential for nuclear deployment.(8) Additionally, while institutional and governance factors were incorporated in a number of prior studies, the effect of these on overall nuclear development potential was not explored in depth. (9-11)

2.3. Data envelopment analysis. Our primary data assessment method, data envelopment analysis (DEA), has been used extensively as a benchmarking technique for efficiency or performance. In the energy space, it has been used to examine plant siting potential (14) and in the assessment of different energy generation technologies.(15) A 2008 study lists over 100 different instances of the use of the technique for energy and environmental studies.(16) However, we believe that this is the first use of DEA in evaluating nuclear development and carbon mitigation potential. Use of this frontier benchmarking technique, and comparison with more basic modeling methods allows us to assess the relative development potential, but also allows us to identify potential policy needs, since the technique identifies the areas of improvement that would allow each nation to become a more viable candidate for development. Our method also demonstrates the critical importance of existing nuclear nations to carbon mitigation, and ties assessments of readiness for development to the broader question of total CO_2 mitigation potential.

3. Method. Full descriptions of our analytic methods are provided in Appendix B. What follows are descriptions of the variables chosen for our analysis and a short description of the analytic basis for DEA.

3.1. Data sources, variable description, and rationale. Data sources and rationale for the use of these data in this assessment are provided in Tables 4-1 and 4-2.(17-21)

Table 4-1. Data description and sources. Rationale for data selection and use in Data Envelopment Analysis is provided.

Category	Variable	Unit	Description	Rationale	DEA Use	Source
Energy	**Fraction New**	Fraction	Fraction of generation that would be attributed to new 100 Mwe SMR	Smaller value (larger grid) indicates greater capacity to incorporate new generation	Input	World Bank Databank - Sustainbable Energy for All
Environment	**Renewable Generation**	GWh	Electric output (GWh) of power plants using renewable resources, including wind, solar PV, solar thermal, hydro, marine, geothermal, solid biofuels, renewable municipal waste, liquid biofuels and biogas.	Higher renewables penetration indicates focus on development of carbon free generation resources	Output	World Bank Databank - Sustainbable Energy for All
	Fossil Generation	GWh	Amount of annual generation attributable to fossil resources	Higher fossil generation reflects greater need for low carbon generation	Output	World Bank Databank - Sustainbable Energy for All
Economics	**Gross Domestic Product**	$2010	GDP is the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products.	Higher GDP reflects greater capacity to develop new energy generation	Output	World Bank national accounts data, and OECD National Accounts data files.
	GDP per capita	Current $	GDP per capita is gross domestic product divided by midyear population.	Higher GDP per capita reflects greater capacity for development, adjusted to reflect population factors that may limit development capacity	Output	World Bank national accounts data, and OECD National Accounts data files.
	Trade Activity	Current $	Combination Import and export acitvity; all transactions between residents of a country and the rest of the world involving a change of ownership from residents to nonresidents of general merchandise, net exports of goods under merchanting, nonmonetary gold, and services.	Higher Trade activity reflects greater exposure to external credit markets and therefore greater capacity to develop new energy projects	Output	International Monetary Fund, Balance of Payments Statistics Yearbook and data files.
Institutions	**Government Effectiveness**	Standard Normal Distribution	Government Effectiveness captures perceptions of the quality of public services, the quality of the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies. Estimate gives the country's score on the aggregate indicator, in units of a standard normal distribution.	Higher ranking reflects higher institutional readiness for nuclear development	Output	World Governance Indicators
	Political Stability	Standard Normal Distribution	Political Stability and Absence of Violence/Terrorism measures perceptions of the likelihood of political instability and/or politically-motivated violence, including terrorism. Estimate gives the country's score on the aggregate indicator, in units of a standard normal distribution.	Higher ranking reflects higher institutional readiness for nuclear development	Output	World Governance Indicators
	Control of Corruption	Standard Normal Distribution	Control of Corruption captures perceptions of the extent to which public power is exercised for private gain. Estimate gives the country's score on the aggregate indicator, in units of a standard normal distribution.	Higher ranking reflects higher institutional readiness for nuclear development	Output	World Governance Indicators

Table 4-2. Data description and sources for fSMR sensitivity analysis. Rationale for data selection and use in Data Envelopment Analysis is provided.

Category	Variable	Unit	Description	Rationale	DEA Use	Source
floating SMR	Coastal	Binary (0,1)	Value equals 1 if nation is a coastal state with adequate ocean access for fSMR deployment, else zero	To deploy fSMR, coastal access to international waterways is required	Screen	Author global access assessment
	Seismicity	#	Number of significant seismic events since the year 1700 using all seismicity scales	Higher seismicity reflects greater need for fSMR which is seismicall isolated	Output	U.S. National Oceanographic and Atmospheric Administration
	Water need	%	Annual freshwater withdrawals, total (% of internal resources)	Higher use of existing resources reflects greater need for energy development that does not require freshwater withdrawal	Output	World Bank Databank; Food and Agriculture Organization, AQUASTAT data.

3.1.1. Economic variable correlation with sovereign credit ratings. In order to ensure that selected variables correctly reflect economic viability for energy development, an assessment was made of sovereign risk ratings that were available for approximately 90 of the nations evaluated across the years assessed. A linear regression was performed to determine how well the three economic factors in Table 4-1 explain the variation in sovereign risk ratings (the dependent variable). R-squared values for the regression indicate 69-74% explanatory power. Prior analysis of sovereign risk also indicates that the inclusion of government effectiveness in the assessment of sovereign risk variance provides additional explanatory power.(21) To assess this, we added one of our institutional variables – Government Effectiveness – to the regression and the results indicated 80-85% explanatory power across the nations assessed. This indicates that, for the purpose of assessing credit worthiness and development viability, our chosen variables should have strong explanatory power for this benchmarking assessment. Regression results for 2007 and 2012 credit rating assessments are provided in Appendix A.

To assess the impact of variable choice and DEA performance benchmark values, the correlation between sovereign credit ratings and DEA performance values for economic factors was also assessed by computing the Spearman rank correlation. Correlations for 2007 and 2012 DEA performance values for economic factors vs. credit ratings were 0.83 and 0.91 respectively, indicating that the DEA method retained the explanatory power reflected in the original regression analysis.

3.2. Method for Data Envelopment Analysis (DEA).

Data envelopment analysis (DEA) is an optimization and benchmarking technique first introduced in 1978 by Charnes, Cooper, and Rhodes. It uses a mathematical programming model that evaluates data based on frontiers, as opposed to central tendencies, as would be done in standard statistical regression models. (23) It has been used in many applications, but predominantly as a tool to perform productivity benchmarking assessments across multiple "Decision-Making Units" or DMUs. In conducting DEA, the "efficiency" or performance of DMUs are measured relative to each other. In most assessments of efficiency, following the Pareto-Koopmans definition, 100% efficiency for a DMU would occur if none of its inputs or outputs can be improved without worsening some other input or output.(24) Because it is often impossible to determine what the theoretical maximum level of efficiency may be for assessments across different organizations, DEA emphasizes only the empirically known information and rates a DMU as efficient only if the performance of other DMUs does not indicate that some inputs or outputs can be improved without worsening others. Therefore, the method makes no assumptions about weights of inputs or outputs, nor does it explicitly specify the formal relation between the inputs and outputs.(23) For purposes of this readiness assessment, we label the benchmark values that emerge from our DEA assessment "performance" scores that compare nations (DMUs) across the range of variables included in the analysis.

DEA analysis, when used in productivity analysis, assumes that there are "n" decision-making units (DMU) which consume varying amounts of "m" different inputs to produce "s" different outputs. As an example, DMU_j consumes x_{ij} of input "i" and produces y_{rj} of output "r." There is an assumption that each DMU has at least one positive input and output value. Efficiency is assessed based on the performance of the DMU in maximizing the ratio of output/input. Each DMU is compared mathematically to find the most efficient performer and final efficiency values are then based on comparison with that most efficient performer which sets the "frontier." A simple case of one input and one output is shown in Figure 4-1 below.

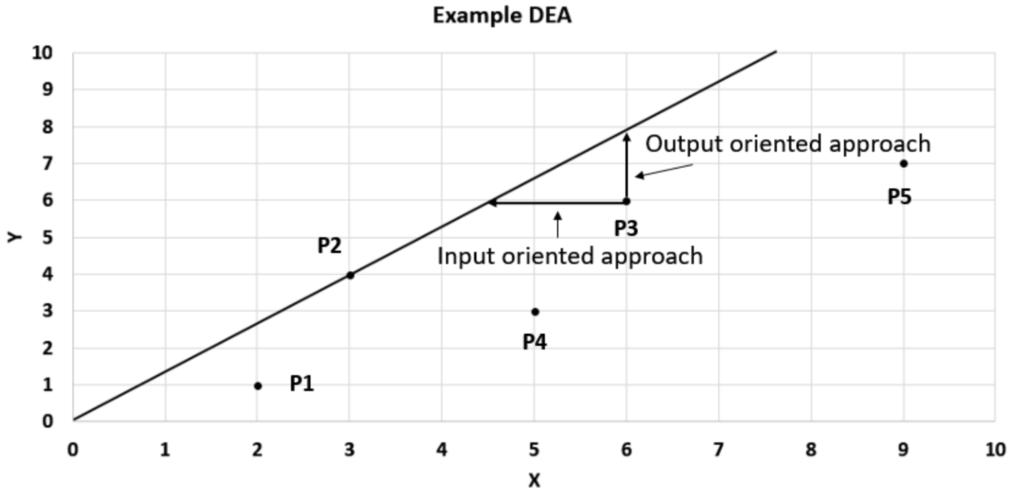

Figure 4-1. DEA Example graph for a single input and single output case. DMU P2 sets the efficient frontier. All other DMUs can be compared for performance against the frontier by following an input or output-oriented approach.

Comparison of performance can be accomplished by evaluation using an “input” oriented approach, where the output is held constant, and inputs are minimized. It can also follow an “output” oriented approach where inputs are held constant, and outputs are maximized. In our analysis, an output-oriented approach is followed. For cases such as ours which are not “productivity” oriented, we leverage the mathematical capacity of the DEA approach to assess various attributes such as GDP or control of corruption to see how nations compare when assessed relative to constant “input” attribute – readiness to develop a single Small Modular Reactor. Our assumption is that readiness for SMR development can be considered a function of Energy, Environmental, Economic, and Institutional factors. Nations that have highest energy need, greatest environmental awareness, and superior economics and institutions will set the frontier in our DEA case and performance of other nations can then be compared to these benchmark nations. When comparing a large number of nations (DMU) across a larger number of attributes, the DEA performance calculation is a bit more complex. This is illustrated in the example below, where we examine the performance of 5 DMUs across three attributes. In this case, attributes Y1 and Y2 are examined for each DMU as they relate to the common attribute X. The comparative example for our analysis is how nations would compare across GDP (Attribute Y1) and Trade performance (Attribute Y2) as factors impacting readiness to develop a single SMR (Attribute X). In this example, DMUs P4 and P5 set the frontier for the two Y attributes. In the standard form of DEA, they are thus assigned performance values of “1.” To calculate the performance of the other three units, we examine their proximity to the frontier, as shown in figure 4-2 which displays the assessment for DMU P2. For this example, through the use of the Pythagorean theorem, we calculate the distances represented by segments A and B and calculate the ratio “B/A,” which in this case yields a value of 1.7 as shown in Table 4-3. In order for DMU P2 to reach the efficient frontier, each of its Y attributes must be multiplied by the factor 1.7 for it to reach the frontier, which is at the point (6.8,3.4). For this case, DMUs P4 and P5 are considered the “peer” group for P2. For P1, the treatment would be similar in the calculation of performance, but because the portion of the horizon that would maximize P1 performance is set by P4 alone, it’s “peer” group is P4 only.

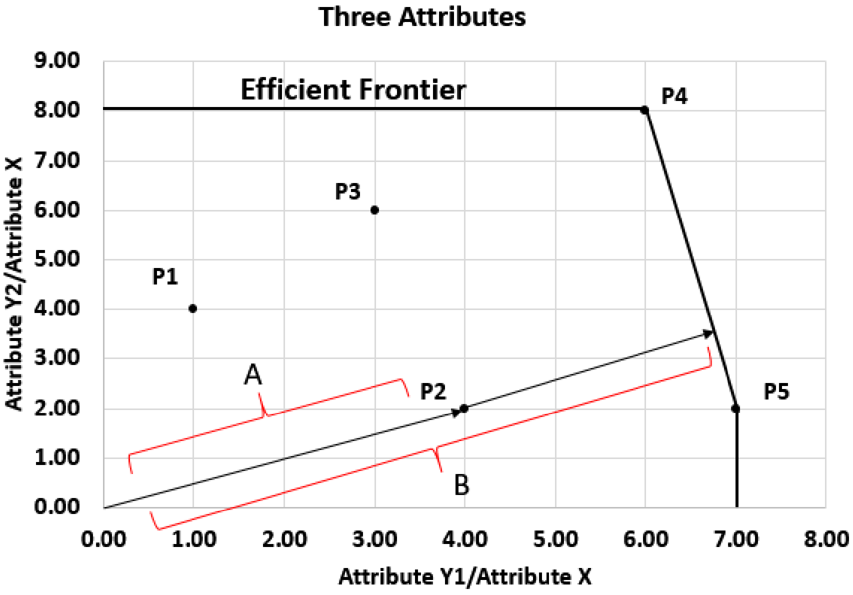

Figure 4-2. DEA assessment of 5 DMUs for three attributes. DMUs P4 and P4 set the efficient frontier. The performance of DMU P2 can be found by assessing distance from the efficient frontier.

Table 4-3. Attribute data and performance values for example case of 5 DMUs using DEA.

	P1	**P2**	**P3**	**P4**	**P5**
Attribute X	1.0	1.0	1.0	1.0	1.0
Attribute Y1	1.0	4.0	3.0	6.0	7.0
Attribute Y2	4.0	2.0	6.0	8.0	2.0
Performance	2	1.7	1.33	1	1
SuperE	2	1.7	1.33	0.64	0.86

To ensure added discriminatory capacity of DEA, an additional process known as "Super Efficiency" may be used which yields greater differentiation across DMUs. This is done by removing the data for the DMU under observation from the dataset during the comparison. An example of this is shown in Figure 4-3. To evaluate DMU P4, which sets the initial frontier, we remove its data from the comparative set and establish a new efficient frontier as shown. We then follow the same procedure to calculate segments A and B. In this case, however, rather than yielding a performance value of 1 or greater, as shown above, P4 is considered to "outperform" and its "super efficiency" is found by (B-A), yielding the SuperE value of 0.64 shown in Table 4-3. A similar computation can be done for P5. As indicated, this allows the greatest discrimination among all 5 DMUs. In this output oriented, super efficiency form of DEA, the lower the performance value, the higher the performance.

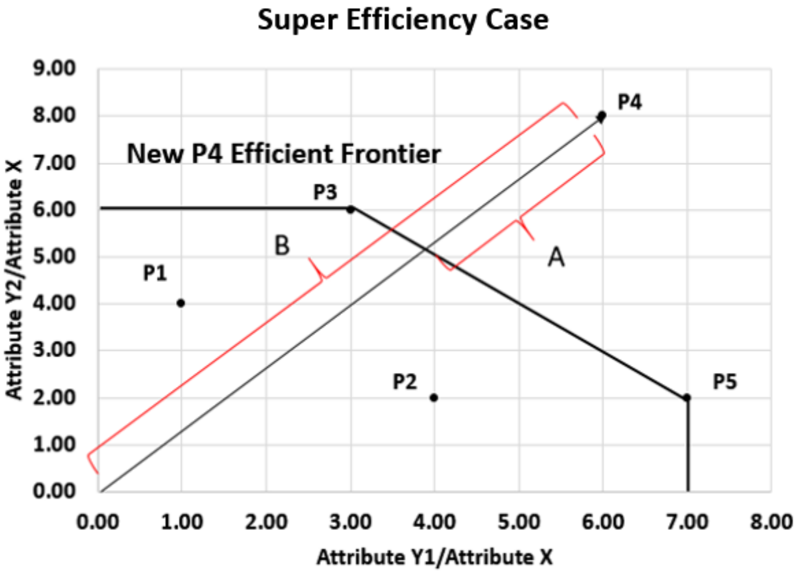

Figure 4-3. Super Efficiency example. DMU P4 is compared vs. a new efficient frontier which is set by removing DMU P4 data from the comparative set. DMU P4 then "outperforms" all others and will have a performance value less than 1.

All DEA modeling was conducted using the R programming language, leveraging the "Benchmarking" R-code package for data analysis.(25) The full mathematical basis for DEA is described in Appendix B.

3.3. DEA Calculations. For the purposes of our analysis, DMUs are nations of the world, and our treatment evaluates the "readiness" of nations for nuclear development. As noted above, from an initial group of 215 nations, 175 were used in the full analysis after removal of 40 nations from the DMU pool due to lack of adequate data. Because DEA is a benchmarking technique, 32 current nuclear nations were used as the core comparative group. All DEA assessments were first conducted on this core group to develop baseline performance within the group. Each of the remaining 143 nations were added, and then removed, sequentially in order to determine a performance score for each as if it were the next to join the existing group of nuclear nations. Each DEA iteration was therefore done within a grouping of 33 DMUs following Constant Returns to Scale (CRS), Variable Returns to Scale (VRS), and Free Disposability (FDH) assumptions. Final performance values reflected high (>90%) correlation between all return to scale scenarios. Since values are comparable and CRS assumptions are more likely to provide maximum discriminatory power between DMUs, **our analysis results reflect super efficiency CRS assumptions**. For further description of these variations, see Appendix B.

As a final discrimination, after assessment, the dataset was reduced to the 125 nations that may have the capacity today, based on fossil generation, to support at least one100 MW_e SMR. The following DEA calculations were conducted:

a. Energy and Environmental Frame – This variant assessed the performance of DMUs using an input of "new SMR as a fraction of installed capacity" and also the addition of a single new SMR to the energy mix for the DMU. Outputs included Fossil Generation and Renewable Generation as described above.
b. Economic Frame – This variant assessed the performance of DMUs using the input of a single new SMR and output of GDP, GDP per Capita, and Trade Activity.
c. Institutional Frame – This variant assessed the performance of DMUs using the input of a single new SMR and outputs of Government Effectiveness, Political Stability, and Corruption.
d. Combined Variables Assessment – This variant combined all Energy, Environmental, Economic, and Institutional variables.
e. fSMR Sensitivity Assessment – This variant was used to determine nations' readiness for floating SMR development using their seismic risk and water scarcity as output factors, and inputs of a single SMR and combined performance rating for all nations from run "d" above.

3.4. Improper Linear Model. As an alternative approach to the evaluation of nations, we also developed a simple linear model using all the same variables used in the DEA process. All variables were given equal weight. A full description of the analytic process is found in Appendix B, and results are provided in the next section.

4. Results.

4.1. Context - SMR Market size. As emphasized in the introduction, our objective is to estimate the global market size for SMRs. While we examined many scenarios, the results described here are for an analysis in which SMRs are used to achieve an 80% level of reduction in current fossil electricity generation. We then examine how our chosen benchmarking performance factors may alter that potential market size. Follow-on results will adjust this scenario based on grid mix, incorporating various lower levels of nuclear generation and reflecting more realistic technology penetration.

Replacing fossil fueled electricity generation in the nations considered with enough reactors to achieve an 80% reduction in CO_2 emissions from power generation would require between 15,000 and 16,000 SMR ($100MW_e$) units in 125 of the 175 nations whose current fossil generation exceeds the annual output of one $100MW_e$ SMR. Figure 4-4 reflects the distribution of this total, with key nations indicated. Note that for simplicity we did not incorporate growth in future electricity demand (although that is a factor that has been considered in other recent assessments of nuclear deployment(9)) nor do we consider the use of SMRs to meet existing or future direct thermal loads.

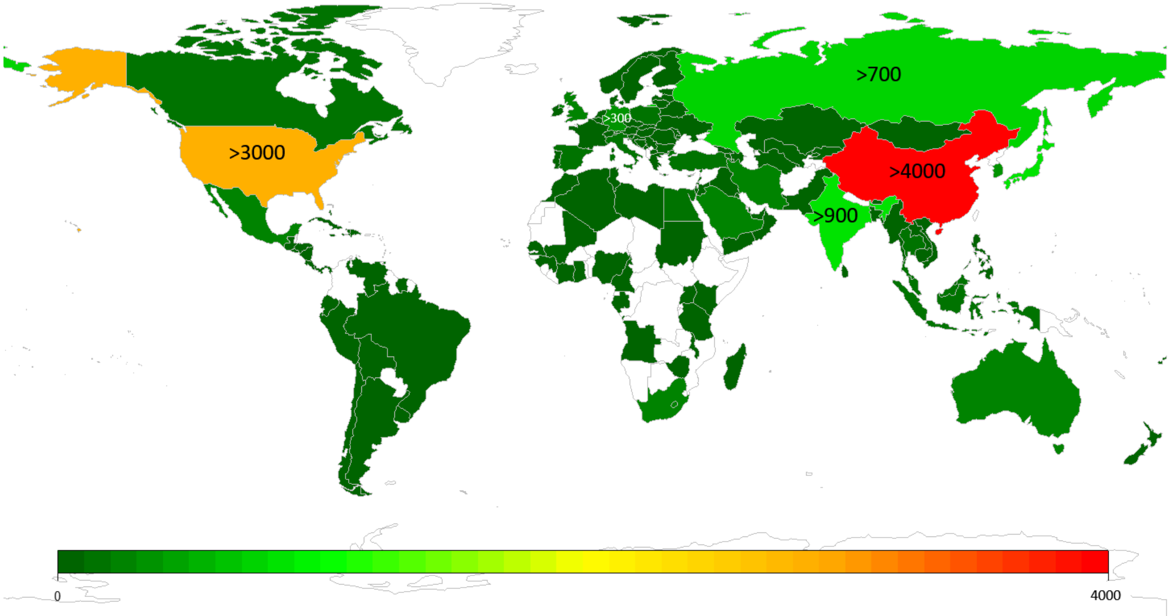

Figure 4-4. Map of SMR Development Potential. Nations colored reflect those that would potentially support development of at least one SMR to reduce fossil electricity generation. Colors reflect the number of $100MW_e$ SMRs that would be required in each country to achieve an 80% reduction in fossil electricity generation.

IAEA guidelines for adding nuclear generation to the electric grid stipulate that no one unit ought to constitute more than 10% of grid capacity to prevent significant grid instability in the event of a single unit outage.(26) Additionally, some of the nations included in the initial screen do not have 1GW of fossil replacement need and would, therefore, be more likely to employ SMRs if developing a nuclear facility. Using these criteria, 54 of the nations considered could support and may opt for the addition of a gigawatt-scale nuclear plant. Historically, utility companies have favored larger units whenever possible, due to a belief in the economies of scale they exhibit. Although this belief has frequently been challenged, until the price and long term operations and maintenance competitiveness of a smaller unit is demonstrated, large-scale development may prevail in larger nations. If these 54 nations ALL chose to move forward with gigawatt-scale deployment, the market potential shrinks to ~172 SMRs as shown in Figure 4-5. Of course, this lower bound assessment does not consider the fact that geographically dispersed installations in nations with larger grids might be better served with an SMR, nor does it consider non-electric applications of SMRs.

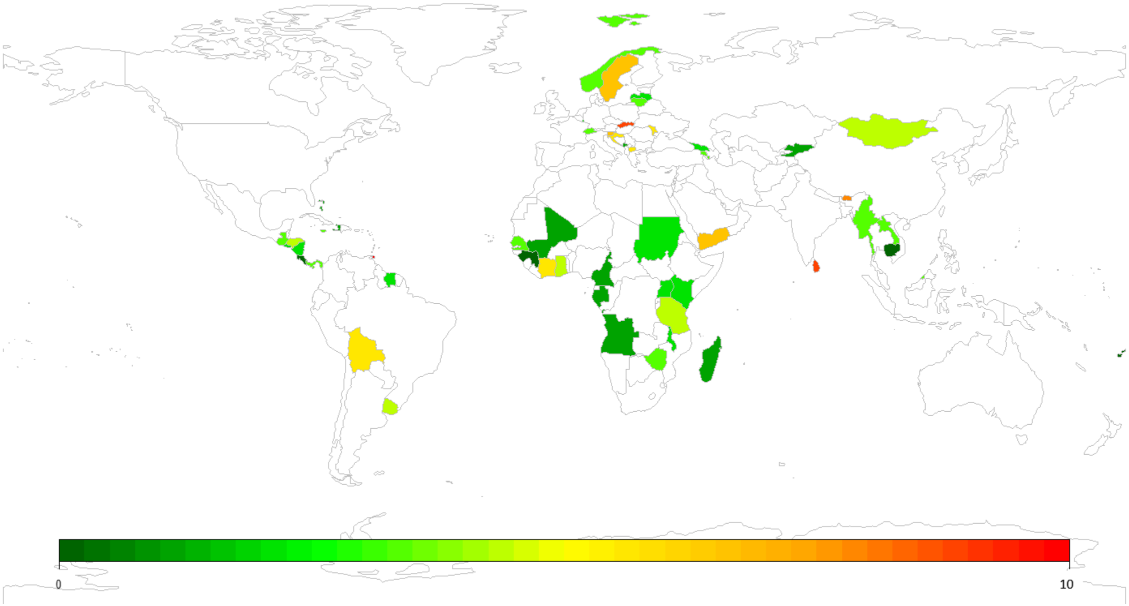

Figure 4-5. Map of low end of SMR development market. Reflects the low end of SMR market size for and 80% fossil reduction scenario. In this display which is complementary to Figure 4-1, all nations with grids large enough to accommodate gigawatt-scale nuclear plants are removed. Remaining nations could absorb only 172 SMRs for electric power generation.

The market range provided here offers only a range for this specific "deep decarbonization" scenario and is not intended to be a predictor of an eventual market size which will be based on national need and more detailed grid assessment. We note that China, Russia, and Argentina have already initiated construction of some small modular designs, and the U.S. is moving forward with development of the NuScale design that will first be deployed at the Idaho National Laboratory.(27) The success of these designs in meeting cost, schedule, and performance goals will have a significant impact on the eventual market demand for this technology.

4.2. DEA Assessment. After bounding the range of potential 100MW$_e$ SMR deployment as between 16,000 and 172 for this "deep decarbonization" scenario, our follow-on assessment uses DEA benchmarked performance to examine how readiness factors may affect the future market size. For display purposes, the figures that follow represent the top two quartiles for performance in each category. We note that in some cases, existing nuclear nations are not in these top quartiles. We do not imply that these nations are not "ready" for further development. Rather, risks exist even within existing nuclear nations and this analysis points to the continued need to assess governance, not just of potential new entrants but also in existing nuclear states. The results for all nations in our pool for 2002, 2007, and 2012 are reported in Appendices C to E, sorted according to combined performance across all variables for those nations that would potentially develop at least one SMR based on final grid screening, which reduced the final results dataset to 125. Table 4-4 below reflects the currently non-nuclear nations that perform above the median for the combined variable assessment.

Table 4-4. Top benchmark performance – non-nuclear nations. Nations that perform above the median composite performance level among current non-nuclear nations. All sub-categories are shown. Lower values reflect higher performance. Values less than one reflect super efficiency. Values of 1 reflect the efficient frontier. Values above one reflect performance that is further from the efficient frontier.

Top Benchmark Performance - Non-Nuclear Nations				
Country	**Energy and Environment**	**Economics**	**Institutions**	**All Variables**
Norway	7.01	0.82	1.00	0.70
Luxembourg	1702.80	0.79	1.01	0.79
Qatar	119.88	0.90	1.05	0.89
Australia	18.54	1.21	1.08	0.90
Singapore	90.11	1.43	1.01	0.98
Denmark	67.96	1.43	0.98	0.98
New Zealand	31.71	2.08	0.98	0.98
Austria	19.68	1.71	1.02	1.01
Barbados	3895.97	5.41	1.05	1.05
Poland	28.79	5.40	1.10	1.05
Bahamas, The	2449.47	3.69	1.06	1.06
Hong Kong SAR, China	107.38	1.97	1.11	1.07
Malta	1841.13	3.77	1.10	1.10
Mauritius	743.26	8.95	1.12	1.12
Ireland	188.46	1.69	1.13	1.13
Brunei Darussalam	1061.65	1.77	1.13	1.13
Bhutan	539.61	33.91	1.17	1.17
Italy	10.93	2.04	1.28	1.17
Portugal	52.05	3.99	1.19	1.18
Lithuania	852.24	5.80	1.19	1.19
Uruguay	154.09	5.51	1.20	1.20
Cyprus	935.01	2.87	1.23	1.23
Chile	39.66	5.38	1.24	1.24
Estonia	397.54	4.77	1.24	1.24
Croatia	199.09	6.28	1.25	1.25
Montenegro	682.60	12.63	1.26	1.26
Mongolia	865.90	19.00	1.29	1.29
Oman	166.69	3.84	1.30	1.30
Latvia	245.30	6.03	1.31	1.31
Israel	66.70	2.55	1.33	1.32
Turkmenistan	234.94	12.23	1.35	1.35
Cuba	235.02	12.80	1.36	1.36
Gabon	1099.45	7.81	1.36	1.36
Vietnam	18.83	20.62	1.40	1.37
Dominican Republic	275.22	13.88	1.40	1.40
El Salvador	268.35	21.21	1.41	1.41
Kuwait	66.56	1.63	1.43	1.42
Malaysia	33.51	6.21	1.50	1.42
Trinidad and Tobago	456.65	4.34	1.46	1.46
Ghana	124.92	46.13	1.46	1.46
Jamaica	1069.00	15.21	1.46	1.46

4.2.1. Energy and Environment. Our first DEA assessment looks at development factors from energy and environment. In this case, the factors with the predominant impact on benchmark performance scores are energy capacity (grid size) and total fossil generation. This drives the largest carbon emitters to the top two quartiles for performance, leading to a market size for SMRs that is only slightly smaller than the total for all 125 nations that have the current fossil replacement need. Figure 4-6 reflects the ranking of the top 62 nations for this frame, indicating that almost 97% of the nuclear capacity required to achieve an 80% reduction could be achieved with 62 nations. For reference, in this and all following figures, performance scores reflect relative rankings for the variables chosen, with smaller values representing performance closer to the most efficient frontier set by the top-performing nation. ***For consistency across all displays,***

column colors reflect the quartile in which nations lie regarding their institutional performance only. This allows us to assess this key area when measured against other factors affecting development readiness.

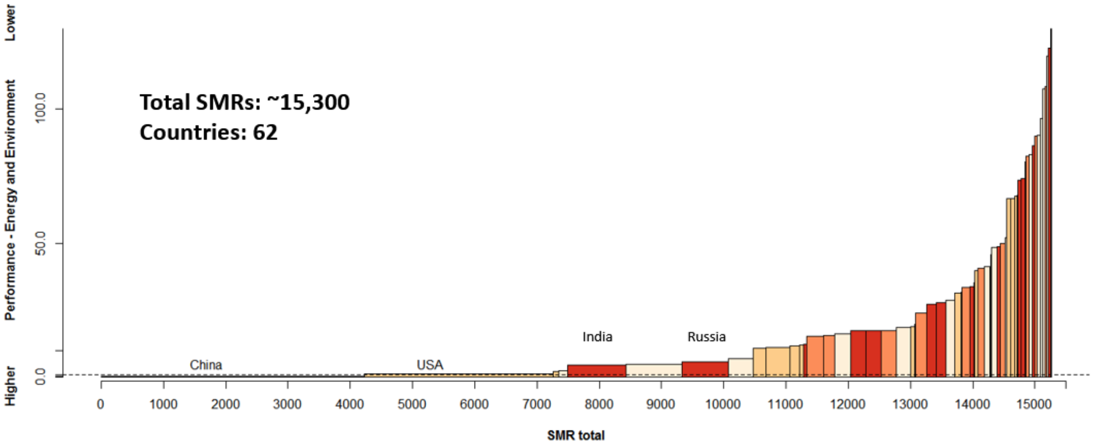

Figure 4-6. SMR market when considering energy and environment. Performance is measured based on energy need, grid size, and renewable energy generation. Lower scores reflect higher relative performance in these areas. Colors reflect quartile performance for Institutional factors – light to dark. Only the top half of performers in the energy and environmental dimension are shown.

4.2.2. Economics. As noted in section 2, economic variables include GDP, GDP per Capita and Trade Activity. Figure 4-7 reflects the performance for the top half of nations considered. Our findings indicate that economic factors may reduce the potential market size for nuclear development somewhat further if development is limited to the top performers.

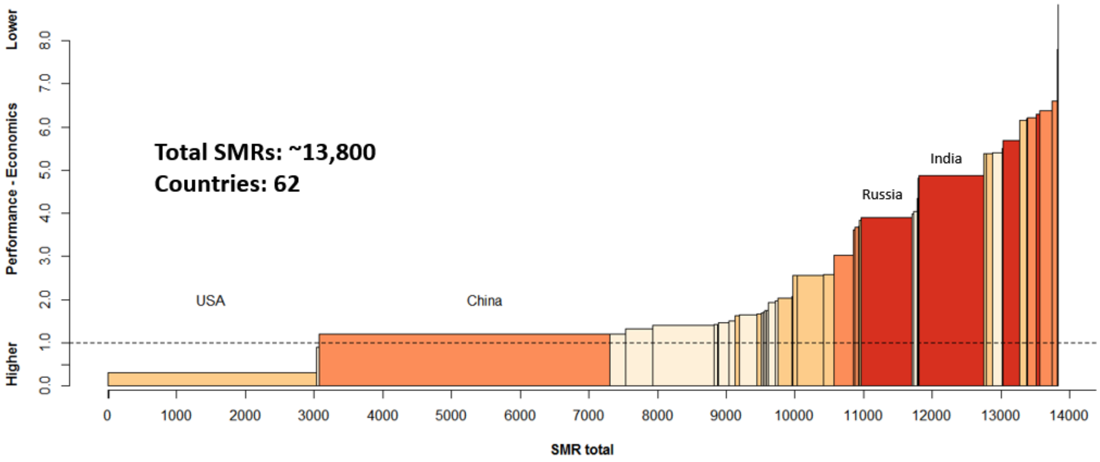

Figure 4-7. SMR market when considering economics. Performance is measured based on relative standing based on GDP, GDP per capita, and trade activity. Lower scores reflect higher relative performance in these areas. Colors reflect quartile performance for Institutional factors – light to dark. Only the top half of performers in the economics dimension are shown.

Eight of the 32 nuclear nations included in our assessment are not included in this mix of top economic performers for 2012. This includes Belarus, one of the two most recent entries to nuclear development. As a result, while this top half of nations accounts for 88% of the scenario benchmark of SMRs, the case of Belarus shows that at least some of the nations with nuclear development may yet add to the potential total.

We also note that four nations in the bottom quartile for institutional performance (Russia, India, Venezuela, and Thailand) appear in the top half of economic performers. These two findings point to the multiple potential pathways that must be considered by policymakers, especially members of the international nuclear control regime, when evaluating nations that might adopt nuclear technology to meet their energy needs. Clearly, there exist nuclear nations willing to assist less-capable ones in acquiring this technology. The policy challenge is to influence these current nuclear states to look at the breadth of factors that may impact readiness, and to separate countries that can manage this technology "in-house" from those that require a different deployment paradigm, such as a "build-own-operate-remove" model, to ensure there is adequate oversight of safety and security.[3]

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[3] Build-own-operate-remove (BOOR) is a development model that envisions vendor nations contracting for power delivery with host nations. The vendor would then build, own, operate, and decommission the plant at the end of life, taking full responsibility for all fuel cycle management.

4.2.3. Institutions. Institutional variables measure government effectiveness, control of corruption and political stability. Nations in the top two quartiles based on performance in these categories are reflected in Figure 4-8. If considering development only in nations that make up the top performers in this category, the market for SMRs would be reduced to 44% of the original market size described in section 4.1. Note that the colors in Figure 4-8 reflect only those in the top half of this category and, as noted previously, these do not include several large nations such as China, Russia, and India. Not only do these three have substantial nuclear capability, but they are also key to climate change mitigation.

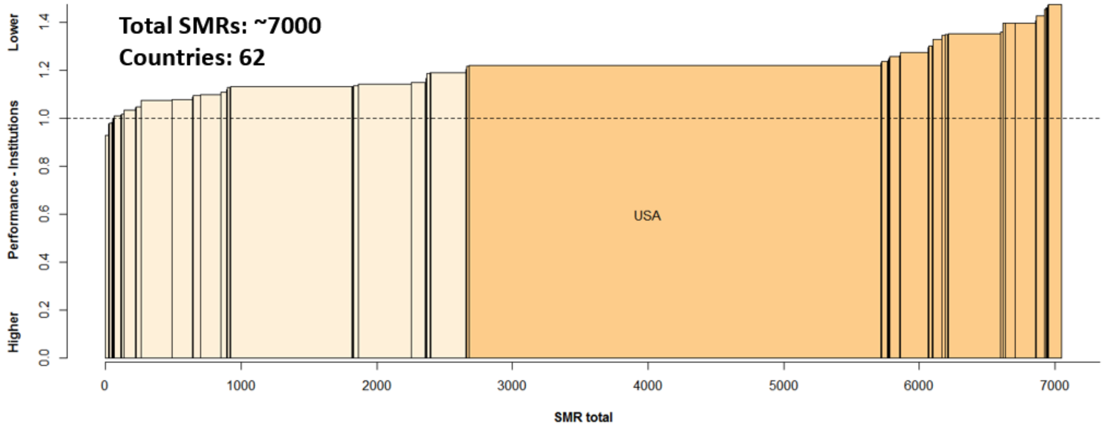


Figure 4-8. SMR market when considering institutions. Performance is measured based on relative standing based on government effectiveness, control of corruption, and political stability. Lower scores reflect higher relative performance in these areas. Colors reflect quartile performance for Institutional factors – light to dark. Only nations that are in the top two quartiles for institutional performance are displayed in this figure.

4.2.4. Combined Assessment. As noted earlier, there are many paths to readiness for nuclear development. To reflect the overall impact of each of the factors included in our assessment, a combined data analysis was conducted using all variables from the previous three categories. Results for the top two quartiles of performers in this assessment are shown in Figure 4-9 below.

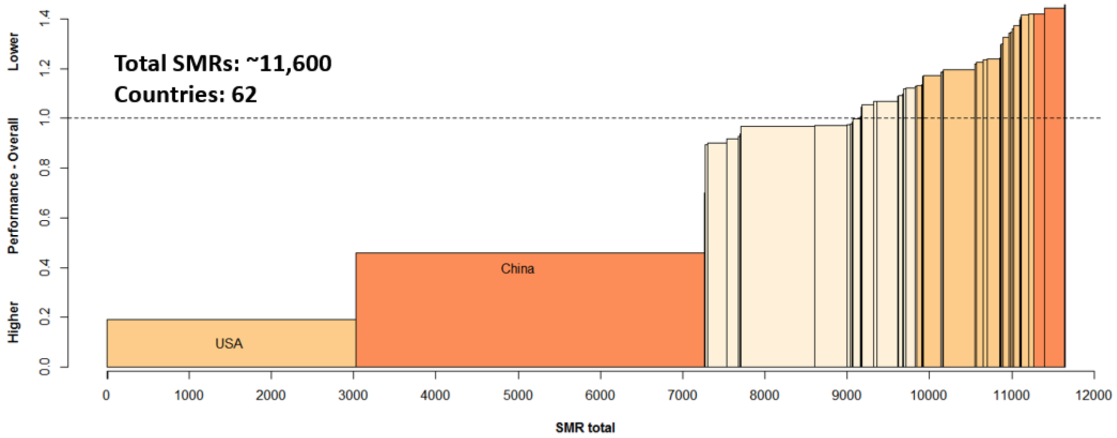


Figure 4-9. SMR market when considering all variables. Top two quartiles shown. Performance is measured based on relative standing across all factors described in Table 4-1. Lower scores reflect higher relative performance across all factors. Colors reflect quartile performance for Institutional factors – light to dark. Only nations that are in the top two quartiles for overall performance are displayed in this figure.

The impact of the incorporation of all factors is an increase in the potential market size to 74% of the original, which was based on fossil generation alone. Major nations that return to the top-performing half include China and South Africa, the two largest red bars in Figure 4-9. The combined effect of incorporating all variables is to balance the very high threshold set by the institutional variables with the economic, energy and environmental factors. Of the nations indicated here, 59 of 62 are in the top half of the institutional rankings. Of the three not among the top institutional performers, China and South Africa are already nuclear capable nations. This is more readily seen in Figure 4-10, which clusters countries according to whether they are currently nuclear or non-nuclear nations.

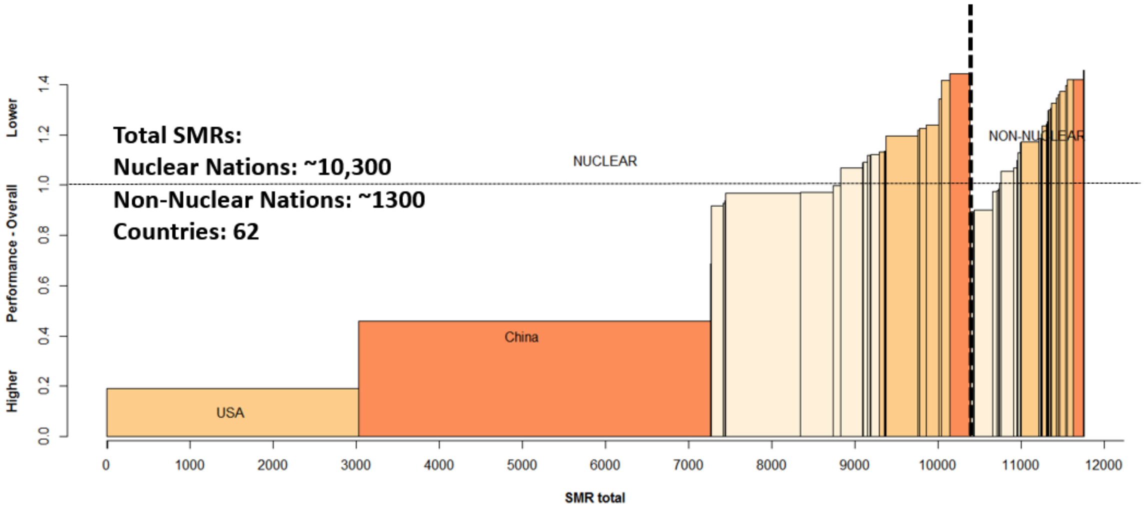


Figure 4-10. SMR market when considering all variables – sorted by nuclear vs. non-nuclear. Performance is measured based on relative standing across all variables described in section 2. Lower scores reflect higher relative performance across all factors. Colors reflect quartile performance for Institutional factors – light to dark. Only nations that are in the top two quartiles for overall performance are displayed.

We noted earlier that nations with larger grids could also undertake development at Gigawatt-scale instead of opting for SMRs. To show the impact that this could have on the size of the SMR market, in Figure 4-11 we have removed those nations that could only support SMR development based on the IAEA 10% of grid guideline. The nations removed accounted for only 18 of the ~11,000 SMRs (<0.2%) in Figure 4-7. This value would ostensibly set the "low end" size of SMR market if development was limited to nations with high institutional performance and all large nations develop at the GW scale for electricity production.

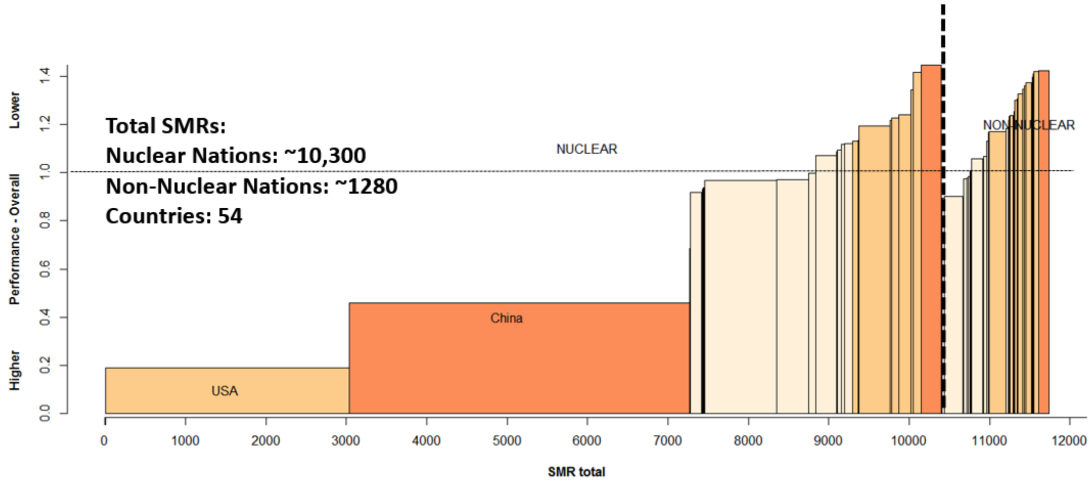


Figure 4-11. SMR market when considering all variables – sorted by nuclear vs. non-nuclear. Grid size >1000MW. Top two quartiles shown. Performance is measured based on relative standing across all variables described in section 2. Lower scores reflect higher relative performance across all factors. Few nations are removed from the mix of potential nations, indicating that the market for "SMR only" is small. Colors reflect quartile performance for Institutional factors – light to dark; Light Green = second quartile; Red = third quartile; and Dark Red = fourth quartile.

In Figure 4-11, we report the 54 nations in the top two quartiles of nations that account for the vast majority of "need" and potential for an SMR market. This includes 23 nuclear nations and the top 31 non-nuclear nations with larger grids. This group could account for over 11,000 SMRs, although realizing an SMR market of this size is unlikely as many would pursue GW scale development. There are also 9 other nuclear nations that might still opt to pursue further development. To reflect this, Figure 4-12 adds these nations back into the mix, showing all nuclear nations and the top non-nuclear nations with a resulting potential for over 13,500 SMRs, or 87% of the original maximum demand for the 80% reduction scenario.

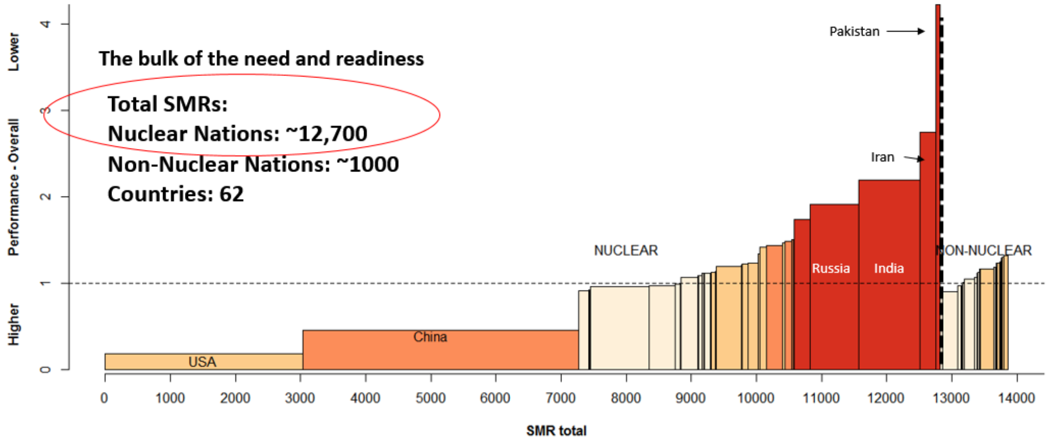


Figure 4-12. SMR market when considering all variables – All nuclear nations plus the top 30 non-nuclear. Performance is measured based on relative standing across all variables described in section 2. Lower scores reflect higher relative performance across all factors. Colors reflect quartile performance for Institutional factors – light to dark; Light Green = second quartile; Red = third quartile; and Dark Red = fourth quartile.

So far, we have speculated on the size of the SMR market that would achieve replacement of 80% of current fossil generation, which given the very modest level of current global action on emissions reduction is almost certainly an unrealistic scenario. Further, any countries will (and should) continue to develop and deploy other forms of clean generation. Some fossil capacity is new and would not likely be replaced in the near term. Finally, grid mix is an important consideration for most nations, and given the complexity of nuclear generation, it is unlikely that most countries would look to achieve "deep" penetration of nuclear akin to the French model (currently >70%). To examine more likely scenarios and their implications for both SMR market size and carbon mitigation, we examined a range of scenarios for grid mix for each nation, beginning with the nominal worldwide average for nuclear nations of ~13% and then increased the nuclear fraction in 10% intervals up to a 50% fractional nuclear component of grid mix. In Figure 4-13, we display these grid penetration scenarios, achieving a maximum SMR market of ~10K and a carbon mitigation of >7.5 Gigatons of CO_2 in the case where 50% of with the electricity is derived from nuclear generation. This equates to a ~23% reduction in global carbon emissions. At 30% nuclear penetration, this technology yields >3.5 Gigatons of CO_2 mitigation. As indicated, the majority of the SMRs in these scenarios would be in the countries that make up the first two quartiles of nations in our overall performance rankings. One-third of these nations are existing nuclear nations, and the lion's share of mitigation comes from deployments in China and the United States, reflecting not only the importance of these two nations to carbon mitigation but also the importance of maintaining the viability of nuclear power in these two markets to support an "economies of volume" argument.

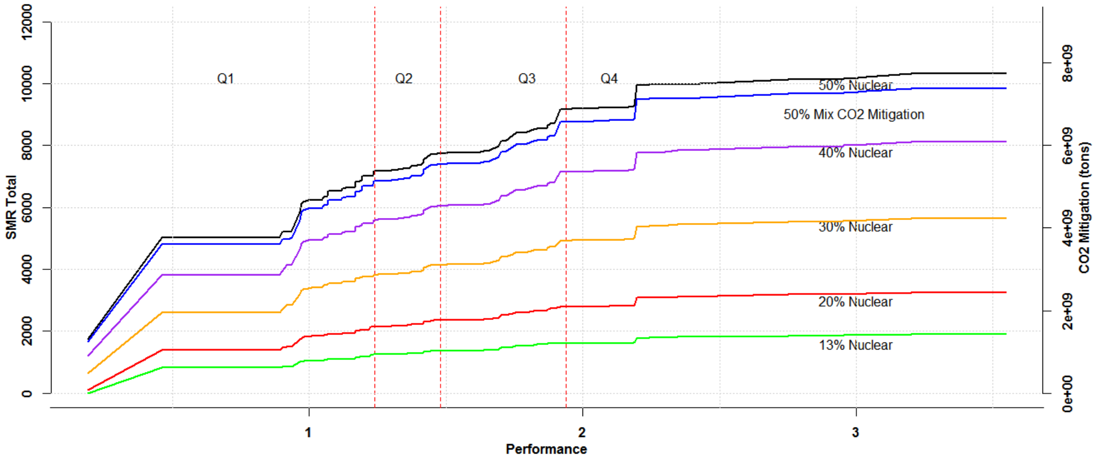


Figure 4-13. Grid Mix Scenarios. Total number of SMRs (left axis) and carbon mitigation potential (right axis) are presented for scenarios of nuclear penetration ranging from 13-50% nuclear portion of grid mix for all nations. The total number of nations included is 117. Quartile breakpoints for DEA performance scores are provided.

Some nations have been backing away from nuclear energy and are unlikely to move ahead with any large-scale development of reactors, including SMRs. At least for the moment this is especially true in the U.S., where low natural gas prices are challenging the long-term viability of even existing nuclear plants.(28) For other reasons, Germany and Japan are both stepping away from nuclear. Some larger non-nuclear nations which have the economic, institutional and grid capacity to support nuclear development have never pursued the technology for political reasons.(29) Given the current development challenges that are evident worldwide, (5) they are unlikely to reverse course anytime soon, let alone become nuclear champions. Notable among these are Australia and Italy, despite the former's significant role in uranium production and the latter's history of research in the nuclear sciences. In Figure 4-14, we calculate the impact on the market of removing these five reluctant nations from the mix of potential

SMR deployers. The impact is dramatic, with an almost 25% reduction in mitigation potential, mostly coming from removing the U.S.

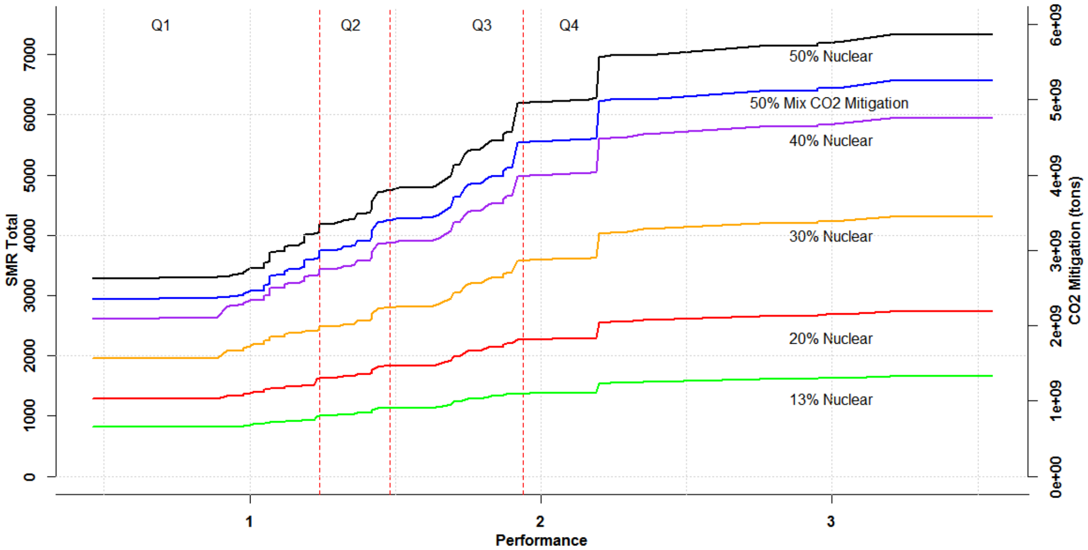


Figure 4-14. Grid Mix Scenarios, removing the five reluctant nations. SMR totals and carbon mitigation potential are presented across scenarios ranging from 13-50% nuclear portion of grid mix for all nations. The total number of nations included is 112, with the U.S., Germany, Italy, Japan, and Australia removed from the dataset that yielded Figure 4-10.

4.2.5. Data assessment. Correlation among variables is a key consideration in regression, and the same is true for DEA. To examine this, we conducted an assessment of correlation using the Pearson, Spearman, and Kendall approaches. Correlation test results are shown in Table 4-5 below for the Spearman test which resulted in the greatest number of correlations.

Table 4-5. Variable Correlation Assessment. Values reflect Spearman Correlation tests for variables used in benchmarking analysis. Values highlighted in red reflect variables with correlations greater than 0.8 or less than -0.8, indicating strong positive or negative correlation.

Variable Correlations									
Spearman									
	Renewable Output	Fossil Generation	Fraction New	GDP Per Capita	GDP	Trade Activity	Gov't Eff	Pol. Stability	Corruption
Renewable Output	1								
Fossil Generation	0.50	1							
Fraction New	-0.73	-0.88	1						
GDP Per Capita	0.24	0.38	-0.45	1					
GDP	0.72	0.82	-0.90	0.58	1				
Trade Activity	0.60	0.78	-0.84	0.62	0.94	1			
Gov't Eff	0.27	0.27	-0.36	0.83	0.48	0.53	1		
Pol. Stability	0.05	-0.03	-0.06	0.70	0.17	0.23	0.76	1	
Corruption	0.17	0.19	-0.27	0.80	0.39	0.43	0.95	0.79	1

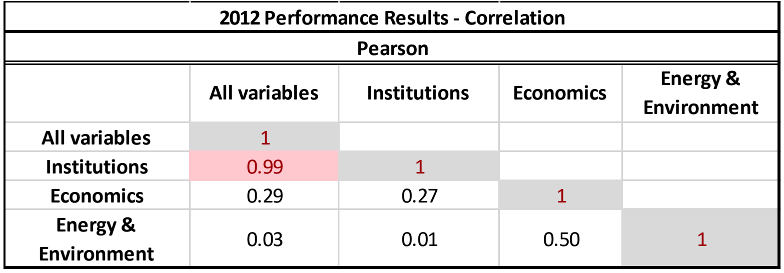
All tests reflected strong correlation between government effectiveness and control of corruption. This correlation is to be expected in that higher levels of government performance normally correspond to strong control of corruption (thus a high index rating). The other common strong correlation is between GDP and trade activity, reflecting an expected relationship between national GDP and international economic activity.

The Spearman test produced a number of other correlations above 0.8, all of which are expected. GDP is correlated with both fossil generation and negatively correlated with the fraction of new generation represented by SMRs. These reflect expected relationships that are based on grid size. Larger nations will have larger grids, which will lead to a smaller "fraction new" and will normally have greater economic activity leading to higher GDP. GDP per capita is positively correlated with government effectiveness, again reflecting the importance of institutions in economic performance. Finally, fossil generation and fraction new are tied, reflecting again a "grid size" factor, where larger grid size (larger fossil generation) will lead to a smaller fraction new. Because of our focus on institutional impact, we were most concerned with the correlation between our institutional variables. To determine the impact of correlation between government effectiveness and control of corruption factors, which showed the highest levels of correlation on both test, each was removed sequentially and the DEA re-conducted. No significant changes were noted in relative nation-state performance. Both variables were still included in the determination of final DEA performance values to provide a balanced number of variables (3) in each sub-category.

4.2.6. Correlation in performance rankings and identifying the frontier. As described in section 3.2, DEA is a benchmarking analysis, leading to one or more of the DMUs assessed setting a "frontier" for the analysis. In the case of our assessment, six nations among the nuclear nations serve as the frontier for comparison across all variables: the United States, Canada, China, Finland, Sweden, and Switzerland. While not all nations would include all six in their "peer group" for assessment, all six serve to set the overall frontier.

In DEA, while each nation essentially finds its most efficient performance relative to the frontier, some variable can have greater impact if evaluating performance across the entire set of DMUs. In evaluating the impact of our chosen variables on overall benchmarked performance, we conducted a correlation assessment that compared the overall performance value of each nation to the individual variables that were used in calculating that performance. Results for the Pearson test are shown in Table 4-6. Correlation with final combined variable performance was strongest for institutional variables, with values >0.9 for all tests. As noted in the section above, to determine if the collinearity of two of the institutional variables (government effectiveness and corruption) had an impact, we removed each from the assessment, executed the DEA model again, and then conducted a follow-on correlation test. Institutional variables were still the most correlated with the final performance value, indicating that when institutional variables are incorporated into the overall envelopment analysis, they have the most significant impact overall, making this an effective method to evaluate readiness for nuclear development if the motive is emphasizing institutional readiness.

Table 4-6. 2012 DEA Performance Results Correlations Tests. Correlation tests were conducted to compare performance results for each sub-category within the DEA assessment and the final all variables combined performance level. Results reflect the strongest correlation of the combined results with the institutional sub-category. Pearson Test results shown. All tests ranged from 90-99% correlation.



2012 Performance Results - Correlation

Pearson

	All variables	**Institutions**	**Economics**	**Energy & Environment**
All variables	1			
Institutions	0.99	1		
Economics	0.29	0.27	1	
Energy & Environment	0.03	0.01	0.50	1

Viewed in the context of data impact on final performance, the Figure 4-15 spider graph represents the slacks of variables from the DEA analysis. Slacks reflect the excess or shortfall of that factor in contributing to a nation's performance. A higher slack value indicates that the nation is further from the efficient frontier for that the variable made a smaller contribution to the nation's final performance level in the benchmark assessment. This spider graph confirms the correlations assessment above, indicating that institutional variables were key to performance when combining all variables. From this assessment, we can conclude that ***top performers will have a combination of a large grid (small fraction new), high GDP per capita, and strong institutions.***

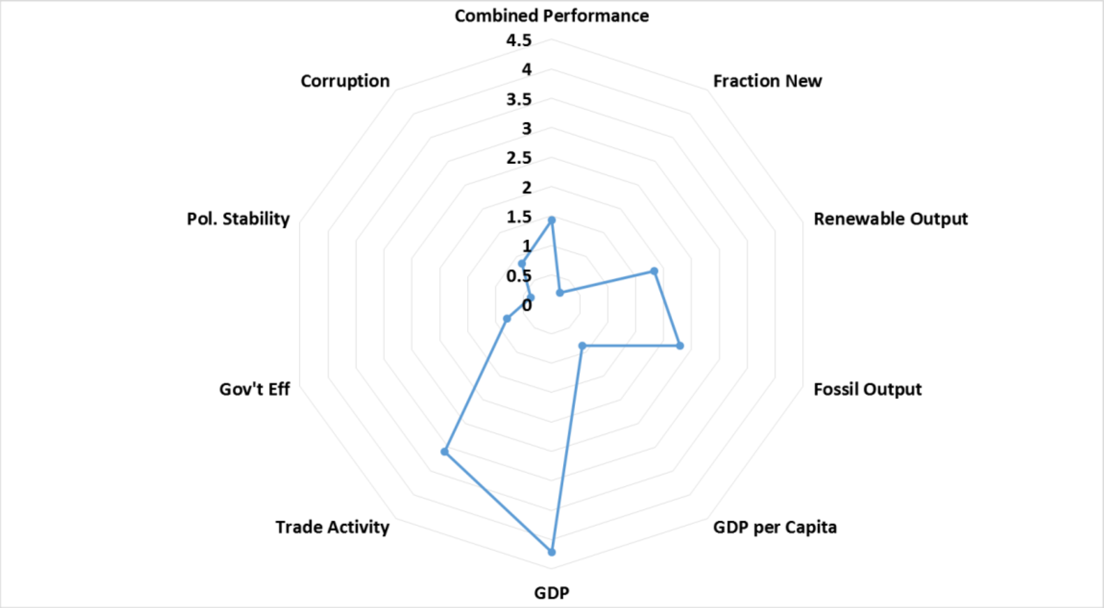


Figure 4-15: Input and Output Slack Averages. The figure represents the average amount of slack, that is, the average relative amount required of each factor for a unit to become efficient. This indicates that the greatest impact on performance comes from “fraction new,” GDP per capita and institutions, where nations are closer to the efficient frontier, therefore requiring less of each to reach full efficiency.

4.2.7. Performance trends. We collected data for our variables from three years (2002, 2007, and 2012) that cover a 10-year period in order to explore temporal trends in the performance of nations using this benchmark method. Trends for a select group of nations that are currently deploying additional nuclear capacity are shown in Figure 4-16. While most nuclear nations have shown relatively stable performance across the years of analysis (and are therefore omitted to simplify the display), some have shown significant improvement, such as China and Argentina. For both these nations, the significant change has been an improvement in economic performance, with stable performance in institutions. China has also consistently been near the top in terms of its need for clean energy. Of the nations shown, the UAE appears as a stable performer. However, while there has been an improvement in institutions, these have been offset by deterioration in its economic factors. This points to the relevance of all three categories in assessing readiness for development. While China is not in the top half of nations for institutional performance, it has significant economic capability and a great need for energy, driving its high benchmark performance in our assessment. The UAE has slipped outside the top half for economic performance, yet a notable improvement in its institutions and its increasing energy needs keep it a strong performer.

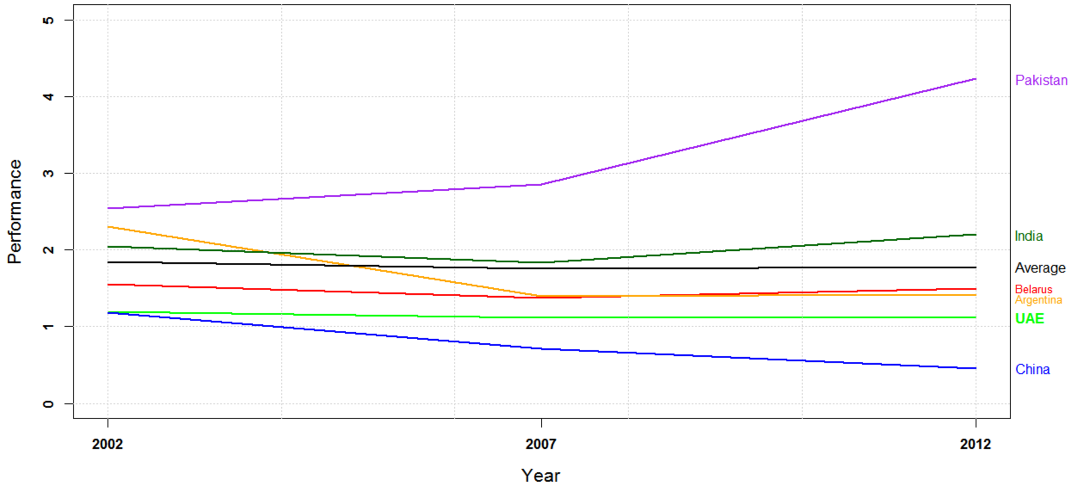


Figure 4-16. Performance Trends for select Nuclear Nations. Trends reflect combined benchmark performance of select nuclear nations shown in three analyzed years. Nations shown are currently developing additional nuclear capacity. Mean Performance: 1.8

Trends can also be examined among currently non-nuclear nations. In 2011, the Survey of Emerging Nuclear Energy States (SENES) explored the potential for nuclear development in a number of currently non-nuclear nations.(30) Among these were the nations shown in Figure 4-17. Using our benchmarking process, a number of these nations have demonstrated potential across the three major readiness areas. One nation that has a significant need, Indonesia, is clearly improving in overall performance due to increased performance in economics and institutions and may be a viable candidate for nuclear development. However, it remains in the bottom half of performers for institutions in our analysis and has yet to meet all the recommended norms for development, including participation in international civil nuclear liability regimes. We note that, of the 30 nations that were identified in the SENES survey, only the eight shown in Figure 4-17 currently outperform the mean for overall performance (Indonesia is the exception). This is largely due to weak institutional performance in the remaining nations.

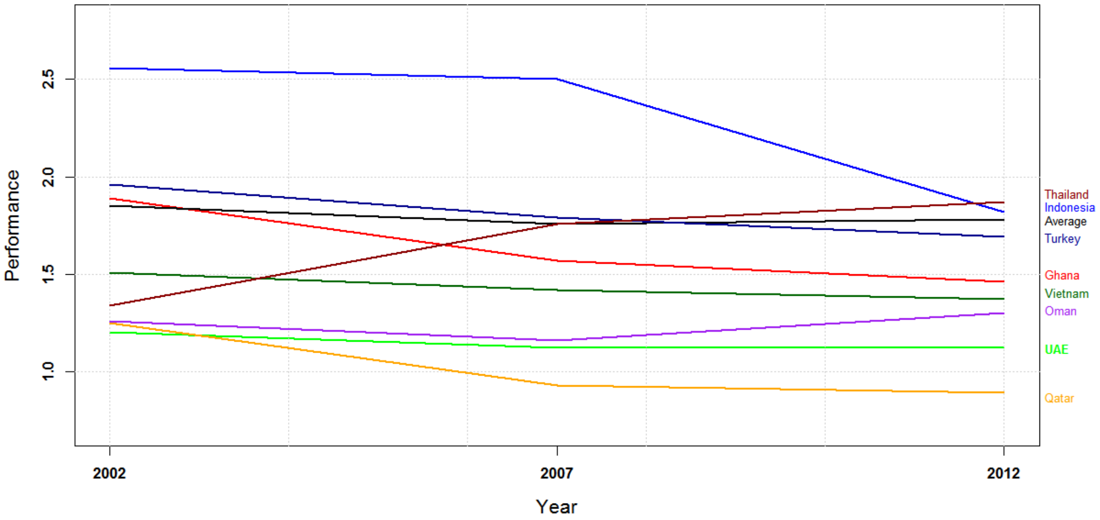


Figure 4-17. Performance Trends – Select Non-nuclear Nations. Trends reflect benchmark performance of nations shown in three selected years. All nations expressed interest in nuclear development, as documented in the 2011 Survey of Emerging Nuclear Energy States. Mean Combined Performance: 1.8

4.2.8. Results with a Linear Linear Model. As an alternative to the DEA approach, we conducted an assessment of the nations in our dataset using an improper linear model.(40) A "proper" model would require a determination of "causation" for the indicators, which is neither feasible nor theoretically sound given the multiple pathways that nations can take to achieve nuclear status. The results of the linear model and a comparison with our DEA results are documented in Appendix G. Correlation of the linear model ranking with the DEA model results was positive, but only at a 69% level. Correlations at the sub-levels of the three key areas were stronger, ranging from 87% for energy and environmental variables to 95% for economic variables. To examine performance within the linear model, rank correlation tests were conducted for the variables versus the combined ranking. Results for the Pearson test, which reported the highest value, are shown in Table 4-7. Unlike the correlations described in section 4.2.5, where institutional variables held sway, the primary correlation using the linear approach is with the economic variables. This was true for all correlation tests. As with the DEA model, higher economic performance is also correlated with higher energy needs. This outcome points to the difference in using an improper linear model that presumes equal weight for all variables and a frontier optimization approach like the DEA method. The latter presumes no fixed weighting among the variables and examines only best possible performance for each unit as compared to the efficient frontier.

Table 4-7. Correlation Test Results – Linear Model. Correlation results for sub-category performance rankings and combined assessment rankings are shown. Strong positive correlation is indicated (~96%) between economic performance and combined performance.

Pearson Test - Linear Model				
	Energy and Environment	Economics	Institutions	Combined Assessment
Energy and Environment	1			
Economics	0.79	1		
Institutions	0.21	0.60	1	
Combined Assessment	0.80	0.96	0.74	1

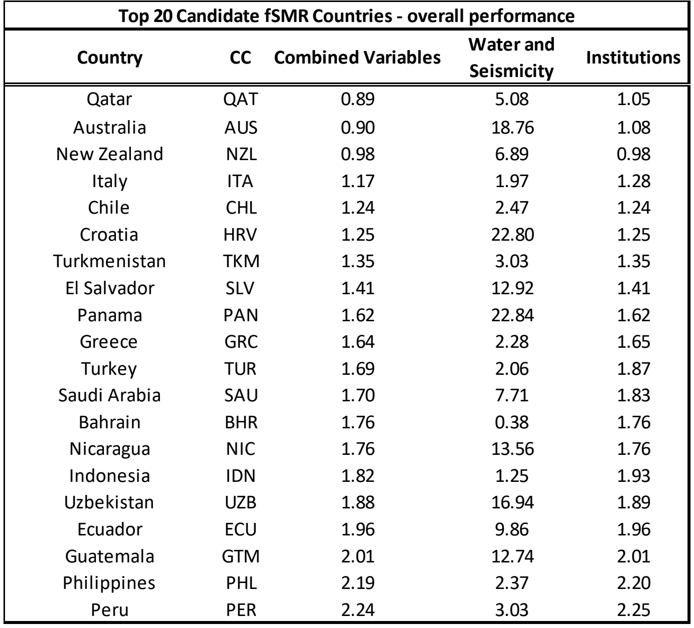
4.2.9. Comparison with prior assessments. As noted in the introduction, a number of prior studies have examined growth potential for nuclear. (9-12) In many cases, the criteria for assessment was similar, with consideration given to economics, need, environment, and governance. Each analysis used a slightly different method than that followed in our assessment, including the Analytic Hierarchy Process (AHP), expert elicitation, and attribute ranking models. Our analysis is unique in that the process dictates no weighting. Comparison of our performance results with these other studies varies widely. Closest in assessment of the "most ready" countries among non-nuclear nations is the 2011 Jewell study, which used an attribute ranking model.(9) There is 80% agreement in the makeup of the top ten best performers. Beyond this, the results are not easily compared as the Jewell analysis includes an assessment of "motivation" which was not a factor in our DEA analysis. Comparison with a recent study from Black and Shropshire (10) reflects reasonable correlation of the nations that make up the top 50 (75% agreement), but very limited correlation in the ranking of performance among these nations (<10%). Finally, comparison with the results of the U.S. Department of Commerce study (11) which used more of a simple linear model/expert elicitation ranking approach reflects only slightly more than 50% correlation of nations the top candidate nations for SMR development (15/27).

4.2.10. Examining the floating Small Modular Reactor (fSMR) option. In assessing the potential for nuclear energy development, it is clear that there are some nations that are well suited to pursue the technology across all dimensions, with pressing energy needs, solid economies and strong institutions. However, even those with strong institutions may not currently have the institutional and human capital necessary to embark on nuclear development immediately. Developing such capability requires much time.

In Chapter 4, we examine the potential of using a build-own-operate-return (BOOR) model for nuclear deployment.(31) Under this paradigm, a floating nuclear plant would be developed and built by a vendor nation that would then deploy the plant to a willing host nation, operate it, then decommission it, taking full responsibility for managing the fuel cycle and providing the human capital required to safely operate the plant in the host nation. In effect, the host nation would "lease" the electricity from the vendor. We envision this option as a more secure alternative to housing nuclear materials in more sites worldwide and claim that, if the need for deep decarbonization becomes pressing, it might prove a viable way of exploiting nuclear power without some of the institutional risks.

To examine the potential for this option, an initial binary data screen was conducted to remove non-coastal nations. We then conducted a separate analysis that incorporated the performance findings from our initial DEA assessments and then added the additional variables of "seismicity" and "water need." The seismicity factor incorporates risk of significant seismic activity that may complicate terrestrial development in the nation. The second variable factors in water scarcity under the assumption that limited fresh water resources would make a floating nuclear plant option more attractive. After all, water availability has been proven to be one of the primary constraints to inland nuclear power plant deployment.(32) After analysis, there are 25 nuclear and 78 non-nuclear nations that were assessed for fSMR viability. The top 20 of these nations (based on seismicity and water need) are listed in Table 4-8. They are ranked in this table according to their overall benchmarked performance values. As noted in our overall results, institutional performance would be a key consideration in evaluating these nations. With a BOOR model, there is potential for mitigation of some institutional risk for nations that might otherwise not be good candidates. In Table 4-8, a nation such as Indonesia stands out as one with significant seismicity and water scarcity, as well as low institutional performance. Indonesia has shown interest in nuclear development and has examined the potential to develop thorium-based reactors that would allow it to exploit its large natural thorium resource. (33,34) Deploying fSMR plants under a BOOR model would give Indonesia near-term nuclear generation while mitigating both natural and institutional risks, especially given that it is among the top 10 greatest CO_2 emitters. We do note that several of these nations have shown a distinct lack of interest in nuclear development and Turkmenistan, though a higher performer, is not even a member of the IAEA. Should energy needs or political mandates to control emissions dictate that any of these nations reconsider, an fSMR might be a viable alternative to the deployment of large-scale terrestrial plants. Detailed results from our analysis of suitability for fSMR deployment are provided in Appendix F.

Table 4-8. Top fSMR Candidates. The table includes the top twenty nations for benchmark performance in water need and seismicity. Nations are ranked according to combined variable performance. Lower scores reflect better performance.



Top 20 Candidate fSMR Countries - overall performance

Country	CC	Combined Variables	Water and Seismicity	Institutions
Qatar	QAT	0.89	5.08	1.05
Australia	AUS	0.90	18.76	1.08
New Zealand	NZL	0.98	6.89	0.98
Italy	ITA	1.17	1.97	1.28
Chile	CHL	1.24	2.47	1.24
Croatia	HRV	1.25	22.80	1.25
Turkmenistan	TKM	1.35	3.03	1.35
El Salvador	SLV	1.41	12.92	1.41
Panama	PAN	1.62	22.84	1.62
Greece	GRC	1.64	2.28	1.65
Turkey	TUR	1.69	2.06	1.87
Saudi Arabia	SAU	1.70	7.71	1.83
Bahrain	BHR	1.76	0.38	1.76
Nicaragua	NIC	1.76	13.56	1.76
Indonesia	IDN	1.82	1.25	1.93
Uzbekistan	UZB	1.88	16.94	1.89
Ecuador	ECU	1.96	9.86	1.96
Guatemala	GTM	2.01	12.74	2.01
Philippines	PHL	2.19	2.37	2.20
Peru	PER	2.24	3.03	2.25

5. Discussion and policy implications.

5.1 The SMR market, carbon mitigation, and institutional impact. We calculated the potential market for small modular reactors through a benchmarking assessment of development readiness that took into consideration clean energy need, economics, and institutional readiness. Results from our assessment suggest that the size of the potential market is quite large when considering energy needs and economic factors alone. However, when institutional readiness is also considered, the size of that market shrinks significantly. While many non-nuclear nations have the capacity to join the group of nuclear nations, the vast majority of need in fossil generation reduction, and largest portion of the market, still resides with the core group of large developed nations that continue to operate nuclear power plants today. Even if nuclear deployment were dramatically expanded, and 30% of existing fossil generation were replaced with nuclear power, the impact in terms of mitigating emissions from the power sector are large but would still leave 80-90% of world emissions to be addressed. We also note that while carbon mitigation potential is large, these results do not factor in two issues that have historically limited development: lack of political support and negative public perception. Beyond the market-based dynamics that are limiting further development in the U.S., many of the viable candidate nations that are identified here will not develop nuclear power plants simply because of dread of the technology.

From a policy standpoint, SMR deployment strategies that focus on emerging nuclear energy states for deep decarbonization are well meaning, but flirt with irrelevance, since the overwhelming share of decarbonization will have to be borne by nations that are already nuclear capable. Large SMR exporters from the existing nuclear nations are not likely to be viable if those nations retreat from domestic use of nuclear. In light of this, at least for the next few decades, a focus on maintaining the viability of nuclear power in existing large markets, like the US, China, and India, might accomplish more for both the technology and climate than seeking to export reactors to emerging nations. As we note in Figure 4-4, these three nations alone could constitute over half the world market for SMRs.

5.2 Development risk. The oversight required to safely and securely build and operate nuclear power plants is substantial, including standards assessment and enforcement, construction quality assurance, safety and security, emergency planning, and materials control and accounting. To examine nations' readiness for nuclear development, the IAEA has developed extensive guidelines for use by non-nuclear nations in self-evaluation and preparation for development.(35,36) The IAEA's estimate is that any new nation considering nuclear power will need at least ten years to develop the institutional capacity to safely manage this technology. Recent assessments by the Center for International Governance Innovation point to the pressing need for absolute commitment to the safeguards that comprise the international nuclear governance regime, concluding that:

> "the deal for aspiring states should be: if you want civilian nuclear power, you have to agree to the highest international standards for avoiding nuclear accidents, nuclear terrorism and diversion of materials to nuclear weapons." (30)

Our assessment provides a path to explore overall readiness against key benchmarks including institutions, recognizing that the path will not be exactly the same for every nation. This is seen in the findings for nations that have ongoing development like China and the UAE. As we note above, China has a significant need for clean energy and overwhelming economic capacity. It can, therefore, overcome perceived limitations in institutional readiness, though even there, concerns regarding institutional competence are salient. Meanwhile, the UAE also can support development economically but had to contract for significant development support across the board with South Korea, aided certainly by strength in institutional readiness but more limited economic prowess. Other nations, despite difficulties, might still find support in development, with Belarus the most recent example. Belarus is not among the top-performing nations, either economically or institutionally. When they initiated a program to develop nuclear energy in 2006, they drew initial interest from the U.S., France, and Russia. According to the World Nuclear Association, they determined that the timeline to develop US technology would be extended due to regulatory delays. Meanwhile, the French design was too large, and its development history is abysmal. Russia offered $9B in loans to support development and is currently building two VVER reactors, to be operational by 2018. The development has created some concerns with neighbors such as Lithuania and Germany, who are concerned about Russian design standards and Belarus's capacity to manage a potential emergency. This drew a review from the IAEA, which confirmed that their standards for safety were sufficient in January of 2017.(37) This review was requested by Belarus, reflecting the type of oversight that will be needed should the group of nuclear nations expand further.

While our analysis does not quantify "risk" per se, we have demonstrated that the factors used have a strong tie to credit rating which drives international credit availability.(8,38) To the extent that nations perform poorly, the path to nuclear development may not be closed, but it may carry greater risk from a financial and institutional standpoint. Prior studies of large projects worldwide have noted that poor governance can be tied to poor schedule and cost performance.(39) While an SMR may not be of the scale of some developments covered in these assessments, it would be a large project for many smaller developing nations. This should be factored into the decision process for any vendor nation and for international bodies such as the IAEA who may be asked to support development. Among those nations that are less stable in governance, there is also the potential for greater risk in proliferation – a key development consideration for the international community. Our initial guideline for variable selection was the IAEA standards for sustainable nuclear development. Given the impact that institutions may have on development and proliferation risk, these standards should be updated to reflect the incorporation of governance factors to assess readiness for sustainable nuclear development.

Finally, a strong argument can be made for conducting more analyses of financial risk, energy policy, and deep decarbonization that treat institutional constraints endogenously, as a growing literature is starting to recognize.(8) Incorporating these institutional constraints, which reflect government competence and political stability, and are thus tied closely to economic credibility, shrinks the nuclear market significantly. While this case is perhaps especially salient for nuclear technologies, given their schedule and cost overruns, which can be exacerbated by poor governance, this might also occur with other large investments, such as CCS and large biogas. It is time for models to reflect these limits to action.

5.3. Future analysis. A major shortcoming with some existing country assessments is that they assume there exists an "optimum" - a theoretical nation with attributes across a range of fields - that all countries should aspire to. We believe benchmarking approaches like ours are more appropriate from a theoretical and methodological point of view since they set attribute-specific frontiers and judge nations against those. Moreover, they can be analytically dissected in a manner similar to regressions, in order to evaluate correlations and alternative indicators and conduct as robust a sensitivity analysis as existing data allow.

In follow-on assessments, we believe additional benchmarking reviews should consider future energy need and economic development potential. While we reduced the final size of our DMU results set to reflect nations that have a fossil replacement need today, it is clear that with population growth, some smaller developing nations would perhaps benefit from more stable, high capacity factor (CF) generation. A review that focuses on that potential would be valuable in assessing future development markets for this technology. Should SMR development begin to expand, additional economic assessments would be in order to evaluate cost and supply chain implications, which are not considered as constraints in this analysis.

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Chapter 4 Appendix A. Regression Results

SUMMARY OUTPUT - Regression for 2012 Economic Variables and Sovereign Risk

Regression Statistics	
Multiple R	0.891262408
R Square	0.79434868
Adjusted R Square	0.785208621
Standard Error	11.55797421
Observations	95

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	46439.29615	11609.82404	86.90848815	4.53027E-30
Residual	90	12022.80911	133.5867679		
Total	94	58462.10526			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	21.91835477	3.210338731	6.827427448	9.81919E-10	15.54045654	28.29625299	15.54045654	28.29625299
MAC2	0.000374586	8.65415E-05	4.328395922	3.88538E-05	0.000202656	0.000546515	0.000202656	0.000546515
MAC9	-3.986E-12	3.04308E-12	-1.309858157	0.193577452	-1.00316E-11	2.0596E-12	-1.00316E-11	2.0596E-12
MAC12	1.3432E-11	4.03062E-12	3.332494	0.001250297	5.42449E-12	2.14396E-11	5.42449E-12	2.14396E-11
POL2	13.12022154	2.067230661	6.346762257	8.70407E-09	9.013307013	17.22713606	9.013307013	17.22713606

MAC2 = GDP MAC9 = GDP per capita MAC12 = Trade Activity POL2 = Government Effectiveness

SUMMARY OUTPUT - Regression for 2007 Economic Variables and Sovereign Risk

Regression Statistics	
Multiple R	0.920152993
R Square	0.846681531
Adjusted R Square	0.839550439
Standard Error	10.29156455
Observations	91

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	4	50302.18714	12575.54678	118.7309855	3.577E-34
Residual	86	9108.801876	105.9163009		
Total	90	59410.98901			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	20.9426095	3.345338301	6.260236668	1.45626E-08	14.29229706	27.59292193	14.29229706	27.59292193
MAC2	0.000381948	8.5887E-05	4.447096463	2.58748E-05	0.00021121	0.000552685	0.00021121	0.000552685
MAC9	-2.65505E-12	1.50097E-12	-1.768893959	0.080457049	-5.63888E-12	3.28772E-13	-5.63888E-12	3.28772E-13
MAC12	1.30155E-11	4.35542E-12	2.988334868	0.003655578	4.35717E-12	2.16738E-11	4.35717E-12	2.16738E-11
POL2	14.82792275	1.991751338	7.444665641	6.92715E-11	10.86845214	18.78739336	10.86845214	18.78739336

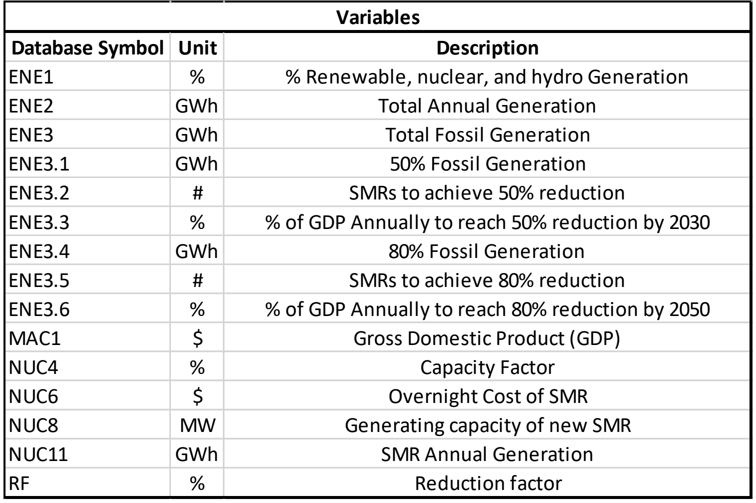
MAC2 = GDP MAC9 = GDP per capita MAC12 = Trade Activity POL2 = Government Effectiveness

Chapter 4 Appendix B. Methods

B.1. Method for range of market size. To evaluate the potential range of the SMR market, data was gathered reflecting the current electricity mix for each nation, isolating the amount that could be attributed to fossil generation. A composite factor was developed for each nation that included the fraction of generation that could be attributed to renewables coupled with the fraction that could be attributed to hydroelectric, nuclear, and geothermal. Using the value for total annual generation (GWh) for each nation, an estimate was made of the generation tied to the burning of fossil fuels for electricity generation. We then estimated the annual generation that would result from a single SMR, assuming a 90% capacity factor (CF) and a 100MWe plant. These factors were then used according to the calculations below to estimate the total number of SMRs to reach 50% and 80% reductions in fossil generation. SMR values reported in the results section reflect totals to achieve an 80% reduction in fossil generation.

B.1.1. Calculations for Market Size (80% scenario shown):

Table B.1. Market Size Variable Descriptions. Variables shown are those included in the calculation of market size for 50% and 80% fossil generation mitigation scenarios.



Variables		
Database Symbol	**Unit**	**Description**
ENE1	%	% Renewable, nuclear, and hydro Generation
ENE2	GWh	Total Annual Generation
ENE3	GWh	Total Fossil Generation
ENE3.1	GWh	50% Fossil Generation
ENE3.2	#	SMRs to achieve 50% reduction
ENE3.3	%	% of GDP Annually to reach 50% reduction by 2030
ENE3.4	GWh	80% Fossil Generation
ENE3.5	#	SMRs to achieve 80% reduction
ENE3.6	%	% of GDP Annually to reach 80% reduction by 2050
MAC1	$	Gross Domestic Product (GDP)
NUC4	%	Capacity Factor
NUC6	$	Overnight Cost of SMR
NUC8	MW	Generating capacity of new SMR
NUC11	GWh	SMR Annual Generation
RF	%	Reduction factor

Fossil Generation (GWh):

$$ENE3 = (1 - ENE1) * ENE2$$

Annual Generation from one SMR (GWh):

$$\frac{NUC8 * 365 * 24 * NUC4}{1000} = NUC11(GWh)$$

Reduction in Fossil Generation (RF = 80%):

$$ENE3.4 = ENE3 * RF$$

SMRs to achieve 80% reduction:

$$ENE3.5 = \frac{ENE3.4}{NUC11}$$

Fraction of GDP to achieve 80% reduction in fossil generation by 2050:

$$ENE3.6 = \frac{ENE3.5 * NUC6}{33} \Big/ MAC1$$

B.2. Method for Improper Linear Model. As an alternative assessment of performance and potential for new development across all nations, we developed a simple linear model. Because the variables under consideration are only indicators of potential viability for nuclear development, a "proper" linear model – one that is based on standard regression techniques – is not possible. A proper model would require a determination of "causation" for the indicators which is not technically feasible (or correct) given the multiple pathways that nations can take to achieve nuclear status. These pathways range from internally driven and funded development to development via outside patronage (e.g. former states of the Soviet Union). However, as Dawes noted many years ago, even an "improper" linear model can provide surprising support to decision makers.(40) Given this, we developed an improper linear model for the variables described above. We performed a simple ranking among the candidate nations for each of the nine factors described in section 2. These rankings were then averaged – giving each variable equal weight – and a final ranking was determined for the nations. We separated the ranking for each of our major sub-categories (Energy and Environment, Economics, Institutions) and also completed a composite ranking.

B.3. Data Envelopment Analysis.

This description is derived from Cooper, et.al.(24) The DEA analysis assumes that there are "n" DMUs which consume varying amounts of "m" different inputs to produce "s" different outputs. As an example, DMU_j consumes x_{ij} of input "i" and produces y_{rj} of output "r." There is an assumption that each DMU has at least one positive input and output value. Efficiency is assessed based on the performance of the DMU in maximizing the ratio of output/input. To assess the relative performance of DMUs, they are each evaluated sequentially relative to the input/output ratios of all other DMUs. The most basic form (named "CCR" for the original developers) reduces multiple output/multiple input combinations for each DMU to a “virtual” single output and input for use in comparison. This virtual set is based on the most efficient “mix” of outputs and inputs for each specific DMU, which is a function of multipliers that are the “variables” in the DEA linear programming (LP) model. The mathematical derivation for the assessment of an individual DMU is as follows:

$$Max\ h_o(u,v) = \frac{\Sigma_r u_r y_{ro}}{\Sigma_i v_i x_{io}}$$

where *u* and *v* are weighting variables and *x*, *y* are the observed inputs and outputs for DMU_o. As all DMUs are evaluated, the virtual output/input ratios are normalized so that ratios for all DMUs are less than or equal to 1. The basis for this overall problem is given by:

$$Max\ h_o(u,v) = \frac{\Sigma_r u_r y_{ro}}{\Sigma_i v_i x_{io}}$$

Subject to the following:

$$\frac{\Sigma_r u_r y_{rj}}{\Sigma_i v_i x_{ij}} \leq 1\ for\ j = 1, \dots, n,$$

$$u_{r,}\ v_i\ \geq 0\ for\ all\ i\ and\ r.$$

This ratio form of DEA is transformed, as described by Charnes and Cooper, to a linear programby adding one constraint (24):

$$\sum_{i=1}^{m} v_i * x_{io} = 1$$

This leads to the following mathematical model for CCR input oriented version known as the multiplier form of DEA:

$$Max\ z = \sum_{r=1}^{s} u_r *\ y_{ro}$$

Subject to:

$$\sum_{i=1}^{s} u_r *\ y_{rj} - \sum_{i=1}^{m} v_i * x_{ij}\ \leq\ 0$$

$$\sum_{i=1}^{m} v_i * x_{io} = 1$$

$$u_{r,}\ v_i\ \geq 0\ for\ all\ i\ and\ r$$

This linear model also has a dual LP form called the envelopment form shown below:

$$min\theta$$

Subject to:

$$\sum_{j=1}^{n} x_{ij} * \lambda_j \leq \theta x_{io} \; for \; i = 1,2,\ldots,m;$$

$$\sum_{j=1}^{n} y_{rj} * \lambda_j \geq y_{ro} \; for \; r = 1,2,\ldots,s;$$

$$\lambda_j \geq 0 \; for \; j = 1,2,\ldots,n.$$

This model also can be written to include/add slacks for the inputs and outputs. This would turn the first two constraints above to equalities.

The DEA model makes some assumptions regarding efficiency comparison. Some DMUs may be found to set the frontier but may do so with "slack" or excess input/output values. DEA ignores slacks in the calculation of efficiency – following a concept of "free disposability" which means that there is no penalty in performance caused by the presence of slacks. In the case of a fully efficient unit (one with an efficiency of "1") there may be slack present. In this case, DEA qualifies the efficiency as "weak efficiency." To be 100% efficient, the resulting efficiency value must be "1" for the DMU and there must be no input/output slacks. As we will describe later, the presence of slacks provides an additional layer of discrimination between DMUs and also provides an evaluative tool to assess where efficiency improvements may be made, even for DMUs that are currently the most efficient in their comparative pool.

The mathematical models above describe an "input" orientation for DEA. An alternative approach is often used that yields the same ability to compare performance but instead follows the inverse ratio of input divided by output with the mathematical objective to minimize the ratio – as opposed to maximizing in the case of the input oriented model. The intuition for the input model is that the outputs are held constant and the goal is to minimize the inputs required. In the output oriented model, the mathematical process is to hold the input constant and maximize the outputs. ***It is the output model that we use in this analysis.*** The **output oriented** model in the **envelopment form**, with slacks included, is shown below:

$$\max \phi - \epsilon * (\sum_{i-1}^{m} s_i^- + \sum_{r=1}^{s} s_r^+)$$

Where ϵ is an arbitrary small, positive number.

Subject to:

$$\sum_{j=1}^{n} x_{ij} * \lambda_j + s_i^- = x_{io} \quad for\ i = 1,2,\dots,m;$$

$$\sum_{j=1}^{n} y_{rj} * \lambda_j - s_r^+ = \phi * y_{ro} \quad for\ r = 1,2,\dots,s;$$

$$\lambda_j \geq 0 \quad j = 1,2,\dots,n.$$

As a final note regarding the base DEA method, the models above (cumulatively called "CCR" models) follow a presumption of constant returns to scale (CRS) – meaning that increases in input will lead to commensurate (scaled) increases in outputs. This presumption can impact the assessment of efficiency for DMUs when there are multiple inputs and output combinations possible, and the functional relationships are not well established. In follow-on development of the CCR model, Banker, Charnes, and Cooper added an additional constraint – reflected in the envelopment model – that the sum of all lambdas equal 1.(41) This added constraint leads to the ability to deal with constant, increasing, and decreasing returns to scale for the variables – also called "variable returns to scale (VRS)." Of note, it is also possible to conduct the analysis with no assumptions regarding returns to scale – removing the assumption of "convexity" for the analysis frontier and only assuming free disposability for slacks. This is called the "FDH" model. (25) In our analysis, we conduct an assessment using all three methods following an output orientation. For reporting purposes, all results are given with the constant returns to scale assumption.

As in the input orientation, the output orientation performance value of "1" reflects maximum efficiency. However, DMUs of lower efficiency using the output model will receive a larger value, effectively the inverse of the efficiency value for the input model. To provide a simple graphical example, consider a single input/single output case following the three returns to scale assumptions described above for five different DMUs (P1-P5). As shown in Figure B.1., with constant returns to scale, a single DMU (P2) sets the frontier, and all other DMUs are compared with it for efficiency. This follows the maximization approach for the output divided by input formulation. P2 will have an efficiency value of “1” with the next most efficient being P3. With variable returns to scale, multiple units may set the frontier, and 4 of 5 DMUs are efficient. For the “No Scale assumption” case, four units again set the frontier. However, the only non-efficient DMU (P4) will have a higher efficiency since it is closer to the frontier. With input orientation, performance values are based on a comparison of input requirements to achieve a comparable output as with DMU P2. For an output orientation, efficiency is measured based on distance from the frontier on the output side, holding the input value constant.

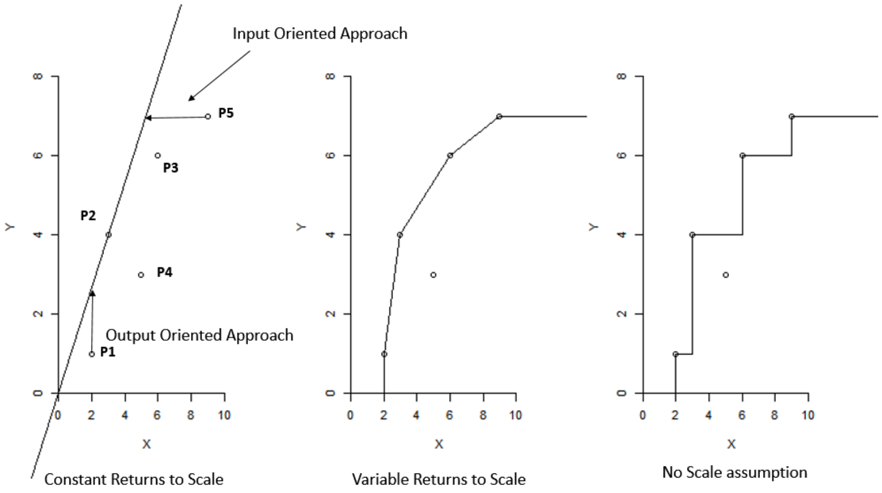


Figure B.1. Return to Scale Examples. Examples of the frontier impact of return to scale assumptions are shown, reflecting constant returns, variable returns, and no scale/free disposability of slacks assumptions.

Efficiency scores for the approaches are shown in Table B.2. following the various scale assumptions.

Table B.2. Sample Performance Scores. The values reflect efficiency scores for DMUs P1-P5 using three return to scale assumptions and both input and output orientations.

Performance Scores						
DEA	Scale	**P1**	**P2**	**P3**	**P4**	**P5**
Input Oriented	CRS	0.38	1	0.75	0.45	0.58
	VRS	1	1	1	0.53	1
	FDH	1	1	1	0.6	1
Output Oriented	CRS	2.67	1	1.33	2.22	1.71
	VRS	1	1	1	1.78	1
	FDH	1	1	1	1.33	1

Super efficiency. One of the challenges with DEA relates to discriminatory power. For a large set of DMUs, there may be multiple efficient units. An efficient DMU can be compared against itself in the standard DEA formulation, leading to the possibility of many DMUs receiving values of "1" or full efficiency. A technique, known as "super-efficiency" can be used to add discriminatory power to DEA by removing the DMU under observation from the comparison set; this is done by adding an additional constraint to the output model described above by assigning a lambda value of zero for that unit ($\lambda_o = 0$). This added constraint leads to an efficiency measure that can be greater than one for the input model and less than one for the output orientation. The intuition for this reflects the amount by which an efficient unit can "outperform" its peers. (24) Regarding results reported in this analysis, a correlation comparison was done of performance values for all nations when conducting standard DEA formulation vs. super-efficiency. A Spearman's rho value of 0.995 was obtained, reflecting almost perfect correlation. To add discriminatory power to our assessment, **all analysis was done using the super efficiency DEA approach.**

To examine the difference between normal DEA and super efficiency, consider the same data shown above. For super efficiency measurement, P2, the most efficient unit, is compared against the frontier established by the next most efficient DMU, P3. All other DMUs are compared with the frontier set by DMU P2. The amount by which P2 "outperforms" the other DMUs is reflected by the distance above the frontier set by P3. Based on this formulation (shown in the output orientation), P2 will have an efficiency value less than one "1" since its output must be reduced to meet the new frontier. All other units will have a performance value greater than one.

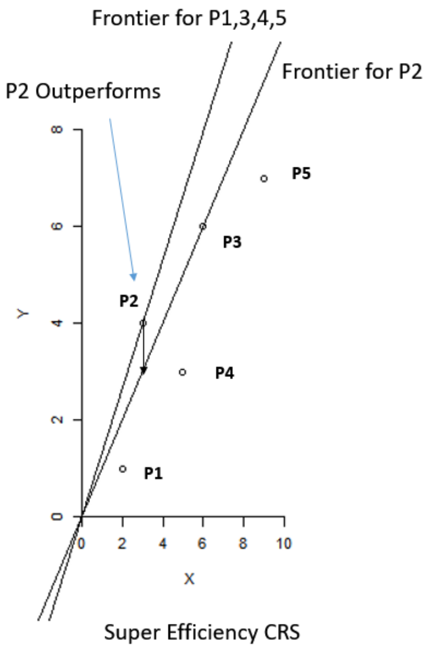


Figure B.2. Super Efficiency Frontier Example. Shown is the impact of a super efficiency approach on the frontier for a constant returns to scale assumption using the same data as in Figure B.1.

Performance Scores for the Output approach for this case are shown in Table B.3. for comparison with the scores above. Note the lower score for P2 with this approach. This adds significant value in cases where there are multiple efficient DMUs and multiple inputs/outputs.

Table B.3. Super efficiency example efficiencies. Reflects efficiency scores for comparison with Table B.I. values when using super efficiency method.

Super Efficiency		**P1**	**P2**	**P3**	**P4**	**P5**
Output Oriented	CRS	2.67	0.75	1.33	2.22	1.71

As an additional example of the DEA process showing actual data from our analysis, we analyzed the number of SMRs that would be required for each current nuclear nation to achieve a 50% reduction in fossil generation (the output) vs. the fraction of gross domestic product required annually for the nation to achieve that target number (the input). Results for the DEA assessment using multiple returns to scale assumptions are shown in Figure B.3. The CRS figure reflects the use of the super efficiency approach. Choice of scale assumption clearly may impact the performance measure and benchmark values for each nation. In our case, however, the final performance values reflected high (>90%) correlation between all returns to scale scenarios. Since values are comparable and CRS assumptions are more likely to provide maximum discriminatory power between DMUs, **our analysis results reflect super efficiency CRS assumptions**.

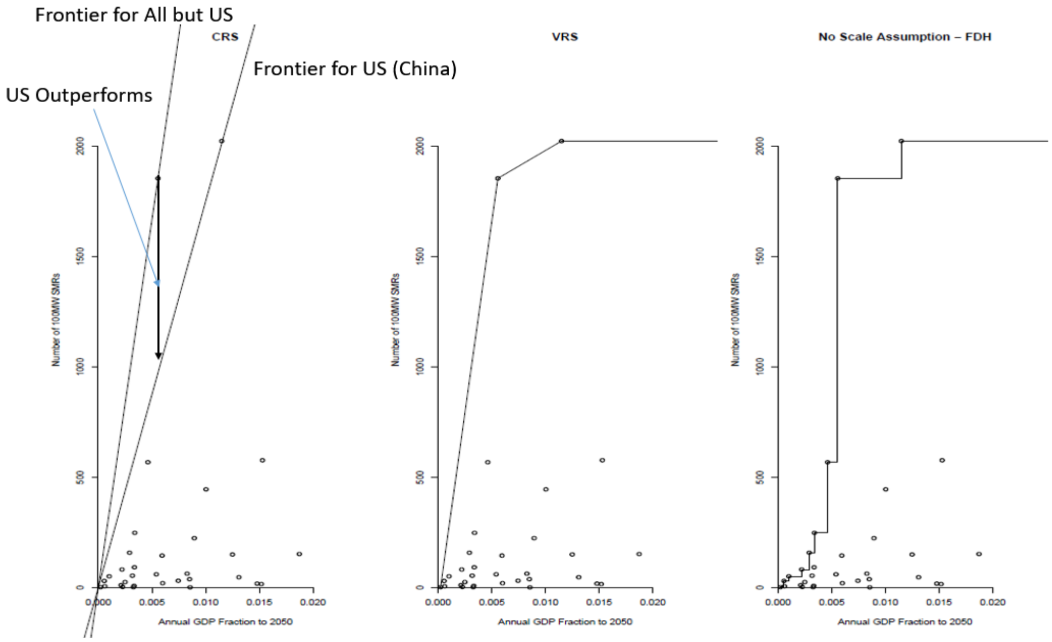


Figure B.3. Frontier examples. Alternative examples showing frontier impacts from various returns to scale assumptions using scenario data.

For additional details of the mathematical basis of DEA, including discussion of optimal solution development, optimization of slacks, data preparation, and derivation of alternative forms, see references (25) and (42-44).

Regarding variable selection, much has been written regarding data selection and the degrees of freedom that result from the combination of the number of DMUs under evaluation (a higher number enhances the degrees of freedom) and the total number of input and output variables incorporated in the assessment (a higher number reduces degrees of freedom). Prior research has indicated that analysis is enhanced when following the following rules of thumb $^{(43)}$:

$$n \geq \max\{m \; x \; s, 3(m+s)\}$$

where n = number of DMUs, m = number of inputs and s = number of outputs. In all our DEA assessments, these rules of thumb are met.

For displays shown in Figures 4-4 and 4-5, the rworldmap Package was used.(45)

Chapter 4 Appendix C. 2002 DEA Results

2002				
Nuclear Nations				
Country	**Energy and Environment**	**Economics**	**Institutions**	**All Variables**
United States	0.22	0.37	1.13	0.10
Canada	0.97	1.67	1.06	0.81
Switzerland	9.96	0.92	1.04	0.83
Japan	3.48	1.24	1.16	0.84
Finland	18.07	1.54	0.95	0.95
Germany	7.61	1.54	1.12	0.96
Sweden	5.06	1.40	1.03	0.98
United Kingdom	9.99	1.35	1.08	1.01
Netherlands	32.84	1.41	1.04	1.02
Belgium	83.26	1.63	1.05	1.03
Spain	10.67	2.37	1.08	1.03
France	5.58	1.64	1.16	1.06
Slovenia	104.88	3.50	1.13	1.13
Hungary	127.84	6.17	1.14	1.14
China	1.19	5.19	2.00	1.19
United Arab Emirates	61.85	1.28	1.26	1.20
Czech Republic	52.50	5.14	1.21	1.21
Brazil	1.21	13.91	1.51	1.21
Slovak Republic	66.04	6.34	1.25	1.25
Korea, Rep.	13.59	3.13	1.44	1.37
Romania	22.28	19.19	1.46	1.42
Bulgaria	146.71	19.84	1.46	1.46
South Africa	14.21	15.78	1.57	1.51
Belarus	109.67	27.72	1.55	1.55
Mexico	10.73	5.52	1.77	1.60
Ukraine	32.01	44.27	2.02	1.82
Russian Federation	2.18	11.91	2.48	1.93
Armenia	216.57	53.01	2.00	2.00
India	4.76	16.24	2.21	2.05
Argentina	9.76	15.80	2.37	2.31
Iran, Islamic Rep.	21.80	21.25	2.58	2.37
Pakistan	15.98	77.53	2.56	2.54

Non-Nuclear Nations				
Country	**Energy and Environment**	**Economics**	**Institutions**	**All Variables**
Luxembourg	1090.37	0.79	1.02	0.79
Norway	2.78	0.96	1.04	0.90
Denmark	52.05	1.24	1.02	1.00
Ireland	123.53	1.26	1.06	1.01
Austria	8.59	1.55	1.05	1.03
Malta	1412.38	3.49	1.03	1.03
Australia	13.83	2.05	1.13	1.04
Singapore	84.77	1.85	1.08	1.07
Portugal	36.48	3.21	1.08	1.08
New Zealand	12.75	2.45	1.11	1.11
Italy	7.32	1.81	1.29	1.14
Mongolia	931.30	72.33	1.16	1.16
Brunei Darussalam	1073.01	2.43	1.17	1.17
Mauritius	760.08	10.45	1.18	1.18
Hong Kong SAR, China	84.46	1.65	1.22	1.18
Chile	14.85	9.01	1.20	1.19
Barbados	3373.93	3.54	1.20	1.20
Bahamas, The	1536.53	1.84	1.23	1.23
Qatar	264.92	1.35	1.30	1.25
Poland	20.74	7.76	1.33	1.25
Latvia	144.79	10.00	1.25	1.25
Estonia	341.09	7.79	1.25	1.25
Cyprus	765.71	2.52	1.26	1.26
Oman	280.53	4.77	1.26	1.26
Greece	57.54	2.93	1.27	1.27
Lithuania	171.13	9.97	1.27	1.27
Uruguay	37.60	10.11	1.30	1.30
Israel	63.74	2.24	1.33	1.33
Thailand	28.74	15.31	1.43	1.34
Bhutan	163.64	46.06	1.36	1.36
Malaysia	42.04	9.42	1.39	1.38
Croatia	66.87	6.83	1.39	1.39
Suriname	480.23	18.64	1.45	1.45
Kazakhstan	39.62	24.66	1.51	1.49
Gabon	386.91	10.04	1.50	1.50
Vietnam	19.74	57.80	1.52	1.51
Mali	747.61	124.42	1.51	1.51
Panama	105.26	10.00	1.55	1.55
El Salvador	168.51	16.97	1.55	1.55
Bahrain	190.01	3.11	1.57	1.57
Cuba	197.78	13.75	1.57	1.57
Tunisia	246.72	17.37	1.58	1.58

Non-Nuclear Nations				
Country	Energy and Environment	Economics	Institutions	All Variables
Montenegro	205.72	19.62	1.60	1.60
Saudi Arabia	20.45	4.91	1.76	1.65
Dominican Republic	303.41	13.73	1.66	1.66
Turkmenistan	270.86	42.62	1.71	1.71
Malawi	326.81	139.22	1.75	1.75
Trinidad and Tobago	515.88	5.86	1.76	1.76
Nicaragua	552.79	40.92	1.81	1.81
Libya	165.32	11.14	1.82	1.82
Kuwait	79.70	2.21	1.90	1.84
Lao PDR	98.29	129.37	1.86	1.86
Ghana	71.49	130.26	1.89	1.89
Bosnia and Herzegovina	68.17	23.67	1.89	1.89
Moldova	535.12	90.12	1.91	1.91
Jamaica	427.59	11.15	1.93	1.93
Madagascar	671.86	156.49	1.93	1.93
Jordan	359.09	21.31	1.95	1.95
Turkey	10.49	11.18	2.02	1.96
Honduras	218.41	34.55	1.97	1.97
Senegal	1327.52	80.44	1.98	1.98
Tanzania	132.36	131.99	1.98	1.98
Morocco	204.23	28.86	1.99	1.99
Bolivia	158.96	45.23	2.02	2.02
Egypt, Arab Rep.	26.93	32.29	2.10	2.07
Lebanon	262.45	7.60	2.09	2.09
Sri Lanka	132.38	46.76	2.13	2.13
Philippines	20.72	38.17	2.16	2.15
Serbia	30.44	18.99	2.27	2.26
Cameroon	113.14	63.49	2.43	2.43
Peru	19.75	19.96	2.50	2.49
Kyrgyz Republic	35.15	128.48	2.52	2.51
Indonesia	21.75	20.05	2.61	2.56
Uganda	206.78	168.74	2.60	2.60
Ecuador	47.82	18.89	2.61	2.61
Guatemala	138.77	24.38	2.71	2.71
Macedonia, FYR	462.37	20.87	2.73	2.73
Algeria	105.04	22.95	2.96	2.95
Kenya	94.22	101.13	3.07	3.07
Bangladesh	161.77	98.04	3.09	3.08
Uzbekistan	56.60	107.26	3.24	3.20
Yemen, Rep.	768.96	72.55	3.43	3.43
Georgia	53.20	53.04	3.62	3.62
Azerbaijan	172.39	54.09	3.69	3.68
Venezuela, RB	6.05	11.21	4.00	3.69
Zimbabwe	94.20	82.59	3.70	3.70
Cote d'Ivoire	206.79	55.98	3.82	3.82
Haiti	1380.86	105.13	3.92	3.92
Nigeria	43.51	70.03	4.28	4.27
Myanmar	169.85	286.47	4.45	4.45
Sudan	278.60	101.81	4.64	4.64
Angola	314.87	52.23	5.22	5.22
Iraq	86.91	118.82	5.48	5.38

Chapter 4 Appendix D. 2007 DEA Results

2007				
Nuclear Nations				
Country	**Energy and Environment**	**Economics**	**Institutions**	**All Variables**
United States	0.69	0.31	1.11	0.13
China	0.71	1.82	1.86	0.71
Switzerland	13.93	0.84	1.00	0.84
Canada	1.34	1.34	1.08	0.87
Japan	4.09	1.56	1.14	0.91
Germany	5.79	1.22	1.11	0.93
Finland	20.90	1.31	0.94	0.94
Sweden	6.56	1.18	1.00	0.96
United Kingdom	9.99	1.15	1.11	1.01
Netherlands	33.72	1.17	1.09	1.06
France	7.67	1.36	1.17	1.09
Slovenia	150.34	2.65	1.11	1.11
Belgium	82.63	1.38	1.12	1.12
United Arab Emirates	41.46	1.47	1.14	1.12
Slovak Republic	102.96	3.93	1.13	1.13
Czech Republic	52.84	3.39	1.14	1.13
Korea, Rep.	11.08	2.43	1.25	1.16
Brazil	1.29	7.28	1.77	1.17
Hungary	130.31	4.44	1.22	1.22
Spain	8.72	1.80	1.37	1.29
South Africa	12.79	9.37	1.43	1.32
Ukraine	31.96	18.01	1.46	1.33
Bulgaria	119.87	10.57	1.36	1.36
Belarus	99.30	13.15	1.38	1.38
Argentina	15.87	8.45	1.47	1.40
Romania	31.74	7.53	1.45	1.41
Armenia	273.71	20.52	1.48	1.48
Russian Federation	2.86	5.44	2.22	1.82
India	3.45	7.73	2.00	1.84
Mexico	13.61	5.54	1.94	1.86
Iran, Islamic Rep.	16.98	12.15	2.37	2.17
Pakistan	17.70	54.03	2.89	2.86

Non-Nuclear Nations				
Country	**Energy and Environment**	**Economics**	**Institutions**	**All Variables**
Luxembourg	1074.82	0.60	1.00	0.60
Norway	3.76	0.74	1.00	0.67
Singapore	77.64	1.55	0.92	0.91
Denmark	49.30	1.08	0.92	0.92
Qatar	162.15	0.94	1.15	0.93
Australia	14.22	1.52	1.06	1.02
Ireland	125.95	1.03	1.09	1.02
Austria	11.72	1.36	1.03	1.03
Hong Kong SAR, China	81.01	1.93	1.04	1.04
Malta	1374.43	3.26	1.06	1.06
New Zealand	17.71	1.94	1.07	1.07
Brunei Darussalam	929.51	1.93	1.08	1.08
Barbados	3242.68	3.84	1.10	1.10
Oman	216.17	3.90	1.16	1.16
Uruguay	61.91	9.02	1.17	1.17
Poland	20.58	5.13	1.25	1.18
Italy	10.65	1.53	1.33	1.18
Mauritius	651.19	9.62	1.18	1.18
Cyprus	648.25	2.01	1.19	1.19
Lithuania	244.84	5.14	1.20	1.20
Portugal	31.32	2.77	1.20	1.20
Bahamas, The	1405.02	2.60	1.21	1.21
Libya	120.29	5.64	1.22	1.22
Mongolia	852.66	38.71	1.23	1.23
Kuwait	64.73	1.40	1.28	1.24
Chile	19.66	5.91	1.24	1.24
Kazakhstan	45.91	9.11	1.27	1.25
Bhutan	77.44	36.02	1.26	1.26
Malaysia	34.67	7.39	1.26	1.26
Israel	58.69	2.53	1.26	1.26
Estonia	261.99	3.81	1.26	1.26
Croatia	118.72	4.67	1.27	1.27
Latvia	179.64	4.50	1.27	1.27
Greece	54.30	2.19	1.29	1.28
Cuba	184.68	12.12	1.33	1.33
Gabon	627.95	7.32	1.40	1.40
Vietnam	21.98	33.33	1.43	1.42
Turkmenistan	212.08	24.25	1.43	1.43
Mali	772.06	106.09	1.43	1.43
Tunisia	231.24	16.46	1.44	1.44
Montenegro	290.29	10.61	1.46	1.46
Malawi	362.04	191.36	1.50	1.50
Madagascar	706.48	162.33	1.52	1.52
El Salvador	155.55	18.83	1.53	1.53
Suriname	583.05	10.79	1.55	1.55
Panama	137.86	10.37	1.56	1.56

Non-Nuclear Nations

Country	Energy and Environment	Economics	Institutions	All Variables
Moldova	570.75	51.38	1.56	1.56
Ghana	136.31	56.06	1.57	1.57
Dominican Republic	244.80	13.58	1.58	1.58
Nicaragua	546.25	46.81	1.59	1.59
Lao PDR	135.24	88.92	1.64	1.64
Trinidad and Tobago	412.13	3.82	1.64	1.64
Jamaica	553.82	13.13	1.65	1.65
Bahrain	145.28	2.99	1.68	1.68
Senegal	1295.97	66.35	1.69	1.69
Jordan	244.12	21.28	1.73	1.73
Saudi Arabia	16.56	3.71	1.87	1.74
Cameroon	129.50	58.28	1.75	1.75
Thailand	23.64	11.66	1.77	1.76
Tanzania	201.27	113.32	1.76	1.76
Turkey	13.93	6.11	1.82	1.79
Macedonia, FYR	502.98	15.56	1.82	1.82
Honduras	213.27	36.74	1.82	1.82
Morocco	168.73	23.82	1.88	1.88
Egypt, Arab Rep.	28.05	31.08	1.95	1.88
Bosnia and Herzegovina	126.97	15.39	1.96	1.96
Serbia	50.61	11.58	1.96	1.96
Georgia	74.51	25.37	1.97	1.97
Azerbaijan	160.94	16.40	2.00	2.00
Philippines	26.97	30.96	2.03	2.03
Angola	203.45	18.94	2.04	2.04
Peru	25.44	17.03	2.11	2.10
Guatemala	121.83	25.40	2.11	2.11
Ecuador	54.94	17.48	2.14	2.14
Bolivia	213.54	45.40	2.19	2.19
Sri Lanka	128.06	37.64	2.24	2.24
Uganda	359.78	149.76	2.34	2.34
Kyrgyz Republic	39.89	87.60	2.40	2.39
Indonesia	24.47	17.94	2.53	2.50
Myanmar	140.37	149.81	2.51	2.51
Venezuela, RB	6.12	7.37	2.71	2.53
Zimbabwe	92.96	157.90	2.55	2.55
Algeria	85.36	15.03	2.57	2.56
Lebanon	274.72	10.51	2.61	2.61
Kenya	105.31	70.28	2.82	2.82
Haiti	3298.79	102.45	2.92	2.92
Uzbekistan	71.71	74.59	3.07	3.04
Bangladesh	104.28	95.04	3.31	3.29
Yemen, Rep.	523.59	61.30	3.49	3.49
Cote d'Ivoire	265.70	56.61	4.74	4.74
Nigeria	81.58	35.16	5.12	5.10
Sudan	350.11	56.14	5.60	5.59
Iraq	88.57	19.30	19.55	19.12

Chapter 4 Appendix E. 2012 DEA Results

2012				
Nuclear Nations				
Country	**Energy and Environment**	**Economics**	**Institutions**	**All Variables**
United States	1.40	0.31	1.22	0.19
China	0.46	1.21	1.91	0.46
Switzerland	24.87	0.69	1.00	0.69
Canada	2.51	1.46	1.08	0.92
Finland	35.33	1.75	0.93	0.93
Sweden	10.26	1.45	0.98	0.94
Japan	4.71	1.41	1.13	0.97
Germany	7.06	1.33	1.14	0.97
Netherlands	48.34	1.51	1.03	1.00
United Kingdom	16.31	1.65	1.19	1.07
Slovak Republic	184.18	4.81	1.09	1.09
Czech Republic	83.11	4.05	1.10	1.09
Belgium	96.41	1.75	1.14	1.12
United Arab Emirates	41.32	1.94	1.15	1.12
France	12.10	1.68	1.26	1.13
Slovenia	233.27	3.70	1.13	1.13
Korea, Rep.	10.97	2.56	1.35	1.19
Hungary	242.68	6.19	1.22	1.22
Brazil	2.21	5.38	1.50	1.23
Spain	11.59	2.57	1.40	1.24
Bulgaria	158.01	11.26	1.34	1.34
Argentina	31.47	6.15	1.47	1.42
South Africa	17.36	9.50	1.53	1.44
Armenia	433.45	23.32	1.46	1.46
Romania	67.55	9.31	1.48	1.47
Ukraine	40.78	16.92	1.58	1.49
Belarus	136.16	11.93	1.51	1.50
Mexico	17.28	5.68	1.94	1.74
Russian Federation	5.66	3.90	2.20	1.92
India	4.52	4.87	2.61	2.20
Iran, Islamic Rep.	17.36	9.94	3.01	2.75
Pakistan	33.77	47.60	4.39	4.23

Non-Nuclear Nations

Country	Energy and Environment	Economics	Institutions	All Variables
Norway	7.01	0.82	1.00	0.70
Luxembourg	1702.80	0.79	1.01	0.79
Qatar	119.88	0.90	1.05	0.89
Australia	18.54	1.21	1.08	0.90
Singapore	90.11	1.43	1.01	0.98
Denmark	67.96	1.43	0.98	0.98
New Zealand	31.71	2.08	0.98	0.98
Austria	19.68	1.71	1.02	1.01
Barbados	3895.97	5.41	1.05	1.05
Poland	28.79	5.40	1.10	1.05
Bahamas, The	2449.47	3.69	1.06	1.06
Hong Kong SAR, China	107.38	1.97	1.11	1.07
Malta	1841.13	3.77	1.10	1.10
Mauritius	743.26	8.95	1.12	1.12
Ireland	188.46	1.69	1.13	1.13
Brunei Darussalam	1061.65	1.77	1.13	1.13
Bhutan	539.61	33.91	1.17	1.17
Italy	10.93	2.04	1.28	1.17
Portugal	52.05	3.99	1.19	1.18
Lithuania	852.24	5.80	1.19	1.19
Uruguay	154.09	5.51	1.20	1.20
Cyprus	935.01	2.87	1.23	1.23
Costa Rica	107.89	8.33	1.23	1.23
Chile	39.66	5.38	1.24	1.24
Estonia	397.54	4.77	1.24	1.24
Croatia	199.09	6.28	1.25	1.25
Montenegro	682.60	12.63	1.26	1.26
Mongolia	865.90	19.00	1.29	1.29
Oman	166.69	3.84	1.30	1.30
Latvia	245.30	6.03	1.31	1.31
Israel	66.70	2.55	1.33	1.32
Turkmenistan	234.94	12.23	1.35	1.35
Cuba	235.02	12.80	1.36	1.36
Gabon	1099.45	7.81	1.36	1.36
Vietnam	18.83	20.62	1.40	1.37
Dominican Republic	275.22	13.88	1.40	1.40
El Salvador	268.35	21.21	1.41	1.41
Kuwait	66.56	1.63	1.43	1.42
Malaysia	33.51	6.21	1.50	1.42
Trinidad and Tobago	456.65	4.34	1.46	1.46
Ghana	124.92	46.13	1.46	1.46
Jamaica	1069.00	15.21	1.46	1.46
Suriname	2058.96	8.83	1.47	1.47
Lao PDR	1115.20	57.54	1.50	1.50
Tanzania	596.92	90.26	1.51	1.51
Moldova	753.69	40.64	1.51	1.51
Malawi	2015.55	215.49	1.52	1.52
Fiji	4999.90	18.30	1.55	1.55
Senegal	1340.46	79.81	1.59	1.59

Non-Nuclear Nations

Country	Energy and Environment	Economics	Institutions	All Variables
Cambodia	1867.03	82.24	1.60	1.60
Panama	186.12	7.79	1.62	1.62
Greece	82.38	3.67	1.65	1.64
Serbia	108.50	14.65	1.66	1.65
Turkey	15.46	6.38	1.87	1.69
Saudi Arabia	15.35	3.02	1.83	1.70
Georgia	139.58	20.07	1.72	1.72
Kazakhstan	49.90	6.60	1.77	1.75
Bahrain	168.36	3.61	1.76	1.76
Nicaragua	584.12	46.82	1.76	1.76
Angola	253.32	14.93	1.77	1.77
Honduras	303.58	34.96	1.79	1.79
Indonesia	24.04	11.72	1.93	1.82
Macedonia, FYR	799.19	17.66	1.82	1.82
Morocco	166.97	25.28	1.84	1.83
Bolivia	389.87	31.44	1.87	1.87
Thailand	27.28	8.83	2.07	1.87
Uzbekistan	89.94	47.04	1.89	1.88
Jordan	252.34	18.80	1.89	1.88
Bosnia and Herzegovina	239.19	18.50	1.90	1.90
Cameroon	219.03	66.42	1.94	1.94
Madagascar	2785.34	180.22	1.94	1.94
Ecuador	80.42	14.48	1.96	1.96
Guatemala	160.16	25.10	2.01	2.01
Azerbaijan	197.01	11.25	2.04	2.04
Sri Lanka	289.71	24.60	2.06	2.06
Tunisia	235.95	19.66	2.10	2.10
Zimbabwe	184.99	97.64	2.15	2.15
Philippines	48.61	24.04	2.20	2.19
Haiti	4212.28	107.98	2.19	2.19
Peru	45.74	12.52	2.25	2.24
Uganda	1466.51	117.53	2.26	2.26
Kyrgyz Republic	71.10	70.60	2.28	2.28
Venezuela, RB	12.29	6.30	2.43	2.35
Myanmar	129.82	69.95	2.36	2.36
Guinea	4747.44	142.79	2.36	2.36
Cote d'Ivoire	543.50	60.70	2.86	2.85
Lebanon	301.77	9.48	2.96	2.95
Algeria	73.45	13.47	2.99	2.95
Kenya	161.83	63.60	2.98	2.98
Bangladesh	86.41	65.83	3.06	3.04
Egypt, Arab Rep.	27.89	21.70	3.34	3.20
Libya	122.72	8.98	3.57	3.55
Mali	2333.28	106.55	5.14	5.13
Iraq	74.10	11.41	5.42	5.32
Nigeria	178.16	21.77	5.78	5.61
Yemen, Rep.	633.86	55.92	9.67	9.64
Sudan	152.32	44.10	9.79	9.74

Chapter 4 Appendix F. Floating SMR Results

Floating Nuclear Benchmark Assessment

Current Nuclear Nations - Coastal

Country	CC	NN	Energy and Environment	Economics	Institutions	All Variables	Water need and Seismicity
United States	USA	1	1.40	0.31	1.22	0.19	0.62
China	CHN	1	0.46	1.21	1.91	0.46	0.69
Canada	CAN	1	2.51	1.46	1.08	0.92	27.08
Finland	FIN	1	35.33	1.75	0.93	0.93	770.95
Sweden	SWE	1	10.26	1.45	0.98	0.94	3030.73
Japan	JPN	1	4.71	1.41	1.13	0.97	1.35
Germany	DEU	1	7.06	1.33	1.14	0.97	66.90
Netherlands	NLD	1	48.34	1.51	1.03	1.00	50.31
United Kingdom	GBR	1	16.31	1.65	1.19	1.07	42.34
United Arab Emirates	ARE	1	41.32	1.94	1.15	1.12	2.14
France	FRA	1	12.10	1.68	1.26	1.13	16.27
Slovenia	SVN	1	233.27	3.70	1.13	1.13	35.37
Korea, Rep.	KOR	1	10.97	2.56	1.35	1.19	103.77
Brazil	BRA	1	2.21	5.38	1.50	1.23	71.74
Spain	ESP	1	11.59	2.57	1.40	1.24	29.73
Bulgaria	BGR	1	158.01	11.26	1.34	1.34	26.74
Argentina	ARG	1	31.47	6.15	1.47	1.42	22.16
South Africa	ZAF	1	17.36	9.50	1.53	1.44	29.63
Romania	ROU	1	67.55	9.31	1.48	1.47	29.52
Ukraine	UKR	1	40.78	16.92	1.58	1.49	59.50
Mexico	MEX	1	17.28	5.68	1.94	1.74	2.46
Russian Federation	RUS	1	5.66	3.90	2.20	1.92	3.01
India	IND	1	4.52	4.87	2.61	2.20	5.08
Iran, Islamic Rep.	IRN	1	17.36	9.94	3.01	2.75	1.60
Pakistan	PAK	1	33.77	47.60	4.39	4.23	6.99

Current Non-Nuclear Nations - Coastal

Country	CC	NN	Energy and Environment	Economics	Institutions	All Variables	Water need and Seismicity
Norway	NOR	0	7.01	0.82	1.00	0.70	418.90
Qatar	QAT	0	119.88	0.90	1.05	0.89	5.74
Australia	AUS	0	18.54	1.21	1.08	0.90	18.76
Singapore	SGP	0	90.11	1.43	1.01	0.98	156.70
Denmark	DNK	0	67.96	1.43	0.98	0.98	457.98
New Zealand	NZL	0	31.71	2.08	0.98	0.98	6.89
Barbados	BRB	0	3895.97	5.41	1.05	1.05	50.86
Poland	POL	0	28.79	5.40	1.10	1.05	203.44
Bahamas, The	BHS	0	2449.47	3.69	1.06	1.06	53.89
Hong Kong SAR, China	HKG	0	107.38	1.97	1.11	1.07	246.98
Malta	MLT	0	1841.13	3.77	1.10	1.10	62.20
Mauritius	MUS	0	743.26	8.95	1.12	1.12	216.13
Ireland	IRL	0	188.46	1.69	1.13	1.13	3720.45
Brunei Darussalam	BRN	0	1061.65	1.77	1.13	1.13	5324.57
Italy	ITA	0	10.93	2.04	1.28	1.17	1.97
Portugal	PRT	0	52.05	3.99	1.19	1.18	38.69
Lithuania	LTU	0	852.24	5.80	1.19	1.19	1482.66
Uruguay	URY	0	154.09	5.51	1.20	1.20	364.58
Cyprus	CYP	0	935.01	2.87	1.23	1.23	121.06
Chile	CHL	0	39.66	5.38	1.24	1.24	2.47
Estonia	EST	0	397.54	4.77	1.24	1.24	467.43
Croatia	HRV	0	199.09	6.28	1.25	1.25	22.80
Montenegro	MNE	0	682.60	12.63	1.26	1.26	64.12
Oman	OMN	0	166.69	3.84	1.30	1.30	70.08
Latvia	LVA	0	245.30	6.03	1.31	1.31	4543.60
Israel	ISR	0	66.70	2.55	1.33	1.32	23.09
Turkmenistan	TKM	0	234.94	12.23	1.35	1.35	3.42
Cuba	CUB	0	235.02	12.80	1.36	1.36	36.59
Gabon	GAB	0	1099.45	7.81	1.36	1.36	433.26
Vietnam	VNM	0	18.83	20.62	1.40	1.37	206.06
Dominican Republic	DOM	0	275.22	13.88	1.40	1.40	30.04
El Salvador	SLV	0	268.35	21.21	1.41	1.41	12.92
Kuwait	KWT	0	66.56	1.63	1.43	1.42	72.21
Malaysia	MYS	0	33.51	6.21	1.50	1.42	140.61
Trinidad and Tobago	TTO	0	456.65	4.34	1.46	1.46	51.27
Ghana	GHA	0	124.92	46.13	1.46	1.46	104.64
Jamaica	JAM	0	1069.00	15.21	1.46	1.46	32.55
Suriname	SUR	0	2058.96	8.83	1.47	1.47	12028.41
Tanzania	TZA	0	596.92	90.26	1.51	1.51	131.81
Senegal	SEN	0	1340.46	79.81	1.59	1.59	939.08
Panama	PAN	0	186.12	7.79	1.62	1.62	22.84

Current Non-Nuclear Nations - Coastal

Country	CC	NN	Energy and Environment	Economics	Institutions	All Variables	Water need and Seismicity
Greece	GRC	0	82.38	3.67	1.65	1.64	2.28
Turkey	TUR	0	15.46	6.38	1.87	1.69	2.06
Saudi Arabia	SAU	0	15.35	3.02	1.83	1.70	8.53
Georgia	GEO	0	139.58	20.07	1.72	1.72	42.85
Kazakhstan	KAZ	0	49.90	6.60	1.77	1.75	41.04
Bahrain	BHR	0	168.36	3.61	1.76	1.76	0.36
Nicaragua	NIC	0	584.12	46.82	1.76	1.76	13.56
Angola	AGO	0	253.32	14.93	1.77	1.77	18735.90
Honduras	HND	0	303.58	34.96	1.79	1.79	43.13
Indonesia	IDN	0	24.04	11.72	1.93	1.82	1.25
Morocco	MAR	0	166.97	25.28	1.84	1.83	25.97
Thailand	THA	0	27.28	8.83	2.07	1.87	102.53
Uzbekistan	UZB	0	89.94	47.04	1.89	1.88	16.94
Jordan	JOR	0	252.34	18.80	1.89	1.88	49.91
Bosnia and Herzegovina	BIH	0	239.19	18.50	1.90	1.90	48.10
Cameroon	CMR	0	219.03	66.42	1.94	1.94	215.67
Madagascar	MDG	0	2785.34	180.22	1.94	1.94	1824.91
Ecuador	ECU	0	80.42	14.48	1.96	1.96	9.86
Guatemala	GTM	0	160.16	25.10	2.01	2.01	12.74
Azerbaijan	AZE	0	197.01	11.25	2.04	2.04	28.66
Sri Lanka	LKA	0	289.71	24.60	2.06	2.06	198.27
Tunisia	TUN	0	235.95	19.66	2.10	2.10	49.24
Philippines	PHL	0	48.61	24.04	2.20	2.19	2.37
Haiti	HTI	0	4212.28	107.98	2.19	2.19	27.99
Peru	PER	0	45.74	12.52	2.25	2.24	3.03
Venezuela, RB	VEN	0	12.29	6.30	2.43	2.35	7.75
Cote d'Ivoire	CIV	0	543.50	60.70	2.86	2.85	207.35
Lebanon	LBN	0	301.77	9.48	2.96	2.95	100.50
Algeria	DZA	0	73.45	13.47	2.99	2.95	7.82
Kenya	KEN	0	161.83	63.60	2.98	2.98	157.80
Bangladesh	BGD	0	86.41	65.83	3.06	3.04	26.11
Egypt, Arab Rep.	EGY	0	27.89	21.70	3.34	3.20	1.98
Libya	LBY	0	122.72	8.98	3.57	3.55	10.47
Iraq	IRQ	0	74.10	11.41	5.42	5.32	28.76
Nigeria	NGA	0	178.16	21.77	5.78	5.61	1506.21
Yemen, Rep.	YEM	0	633.86	55.92	9.67	9.64	38.62
Sudan	SDN	0	152.32	44.10	9.79	9.74	11.83

Chapter 4 Appendix G. Linear Model Ranking vs. DEA

Country Name	Country Code	Nuclear nations	LM Energy and Environment Rank	DEA Energy and Environment Rank	LM Economics Rank	DEA Economics Rank	LM Institutions Rank	DEA Institutions Rank	LM Overall Rank	DEA Combined Rank
			Correlation Values							
			0.95		0.87		0.93		0.69	
Argentina	ARG	1	24	30	42	53	74	63	46	59
Armenia	ARM	1	82	98	105	98	69	59	85	64
Belarus	BLR	1	70	64	66	75	88	69	75	71
Belgium	BEL	1	42	56	18	20	19	26	26	26
Brazil	BRA	1	14	3	28	46	64	65	35	40
Bulgaria	BGR	1	53	68	68	72	56	48	59	52
Canada	CAN	1	11	4	9	13	11	15	10	8
China	CHN	1	1	1	27	6	78	94	35	2
Czech Republic	CZE	1	42	52	37	40	32	17	37	24
Finland	FIN	1	42	34	29	21	3	1	25	9
France	FRA	1	17	14	11	17	27	41	19	30
Germany	DEU	1	7	9	9	8	18	27	11	12
Hungary	HUN	1	64	87	45	54	40	34	50	39
India	IND	1	4	5	45	44	93	115	47	109
Iran, Islamic Rep.	IRN	1	21	20	59	70	104	120	61	116
Japan	JPN	1	5	6	7	9	19	23	10	11
Korea, Rep.	KOR	1	24	12	17	28	39	50	26	37
Mexico	MEX	1	15	19	31	50	75	98	40	84
Netherlands	NLD	1	30	39	12	14	9	10	17	16
Pakistan	PAK	1	30	33	73	111	115	124	73	124
Romania	ROU	1	38	45	54	67	69	64	54	67
Russian Federation	RUS	1	5	7	23	38	98	107	42	98
Slovak Republic	SVK	1	64	75	48	43	35	16	49	23
Slovenia	SVN	1	75	82	55	35	29	25	53	32
South Africa	ZAF	1	36	21	43	69	61	72	47	62
Spain	ESP	1	14	13	18	29	42	55	25	44
Sweden	SWE	1	37	10	16	12	6	2	20	10
Switzerland	CHE	1	53	26	13	2	4	5	23	3
Ukraine	UKR	1	27	36	59	86	93	74	60	69
United Arab Emirates	ARE	1	57	37	25	23	27	28	36	28
United Kingdom	GBR	1	14	18	10	16	26	32	17	22
United States	USA	1	2	2	4	1	24	35	10	1

Country Name	Country Code	Nuclear nations	LM Energy and Environment Rank	DEA Energy and Environment Rank	LM Economics Rank	DEA Economics Rank	LM Institutions Rank	DEA Institutions Rank	LM Overall Rank	DEA Combined Rank
			Correlation Values							
			0.95		0.87		0.93		0.69	
Algeria	DZA	0	58	48	61	80	97	119	72	119
Angola	AGO	0	97	90	67	84	108	84	90	88
Australia	AUS	0	18	22	13	7	13	14	15	7
Austria	AUT	0	38	24	23	19	14	9	25	17
Azerbaijan	AZE	0	67	79	71	71	105	101	81	103
Bahamas, The	BHS	0	118	124	85	34	21	13	75	20
Bahrain	BHR	0	82	73	65	32	65	81	71	86
Bangladesh	BGD	0	62	53	82	116	109	121	84	121
Barbados	BRB	0	123	126	96	48	14	11	77	18
Bhutan	BTN	0	100	100	120	104	35	29	85	33
Bolivia	BOL	0	87	96	97	103	88	89	91	93
Bosnia and Herzegovina	BIH	0	70	86	95	89	81	93	82	97
Brunei Darussalam	BRN	0	104	112	72	22	32	24	69	31
Cambodia	KHM	0	112	120	108	121	97	76	106	77
Cameroon	CMR	0	97	81	103	117	109	96	103	99
Chile	CHL	0	36	35	42	45	30	38	36	43
Costa Rica	CRI	0	86	58	74	62	39	37	66	42
Cote d'Ivoire	CIV	0	89	101	99	114	112	116	100	117
Croatia	HRV	0	73	80	61	56	44	40	59	46
Cuba	CUB	0	72	84	77	79	59	51	69	54
Cyprus	CYP	0	96	111	66	30	27	36	63	41
Denmark	DNK	0	76	46	22	11	10	3	36	14
Dominican Republic	DOM	0	76	92	76	81	80	53	77	57
Ecuador	ECU	0	60	50	71	82	93	99	75	101
Egypt, Arab Rep.	EGY	0	26	28	68	96	106	122	67	122
El Salvador	SLV	0	95	91	95	95	67	56	86	58
Estonia	EST	0	80	97	67	42	33	39	60	45
Fiji	FJI	0	124	129	112	88	85	73	107	75
Gabon	GAB	0	110	114	95	61	85	52	97	55
Georgia	GEO	0	76	65	100	93	62	80	79	83
Ghana	GHA	0	77	62	88	108	61	60	76	65
Greece	GRC	0	38	51	39	33	65	78	47	79
Guatemala	GTM	0	79	69	85	101	97	100	87	102
Guinea	GIN	0	125	128	124	127	114	113	121	115
Haiti	HTI	0	117	127	120	125	117	106	118	108
Honduras	HND	0	85	95	101	105	96	85	94	89
Hong Kong SAR, China	HKG	0	70	57	24	24	13	20	36	21
Indonesia	IDN	0	21	25	48	74	88	95	52	90
Iraq	IRQ	0	49	49	59	73	122	126	76	126
Ireland	IRL	0	59	78	25	18	19	22	34	29
Israel	ISR	0	57	44	36	27	55	47	49	51
Italy	ITA	0	11	11	14	25	48	43	24	34
Jamaica	JAM	0	99	113	96	85	64	61	87	66
Jordan	JOR	0	82	89	87	90	67	91	79	96
Kazakhstan	KAZ	0	40	41	52	59	90	83	61	85
Kenya	KEN	0	88	70	93	115	108	118	97	120
Kuwait	KWT	0	65	43	36	15	62	57	54	60
Kyrgyz Republic	KGZ	0	78	47	118	119	107	111	101	112
Lao PDR	LAO	0	99	115	117	113	94	66	104	70
Latvia	LVA	0	91	88	68	52	43	46	68	50
Lebanon	LBN	0	82	94	72	68	103	117	86	118
Libya	LBY	0	75	61	61	66	126	123	87	123
Lithuania	LTU	0	86	109	61	51	37	31	61	36
Luxembourg	LUX	0	101	118	37	3	8	8	49	5
Macedonia, FYR	MKD	0	89	108	101	87	68	86	86	91
Madagascar	MDG	0	119	125	120	128	100	97	113	100
Malawi	MWI	0	118	121	125	129	79	71	107	74

Country Name	**Country Code**	**Nuclear nations**	**LM Energy and Environment Rank**	**DEA Energy and Environment Rank**	**LM Economics Rank**	**DEA Economics Rank**	**LM Institutions Rank**	**DEA Institutions Rank**	**LM Overall Rank**	**DEA Combined Rank**
			Correlation Values							
			0.95		**0.87**		**0.93**		**0.69**	
Malaysia	MYS	0	32	32	39	55	50	67	40	61
Mali	MLI	0	119	123	117	124	113	125	116	125
Malta	MLT	0	110	119	77	36	24	18	70	25
Mauritius	MUS	0	103	106	93	65	31	21	75	27
Moldova	MDA	0	100	107	113	106	84	70	99	73
Mongolia	MNG	0	106	110	105	91	75	44	95	48
Montenegro	MNE	0	105	105	108	78	52	42	88	47
Morocco	MAR	0	65	72	73	102	77	88	72	92
Myanmar	MMR	0	76	63	103	118	117	112	99	114
New Zealand	NZL	0	49	31	63	26	5	4	39	15
Nicaragua	NIC	0	99	102	110	109	95	82	101	87
Nigeria	NGA	0	60	74	62	97	120	127	81	127
Norway	NOR	0	46	8	19	4	5	6	23	4
Oman	OMN	0	79	71	56	37	49	45	62	49
Panama	PAN	0	83	77	72	60	68	77	74	78
Peru	PER	0	47	38	62	77	84	109	65	110
Philippines	PHL	0	36	40	66	99	87	108	63	107
Poland	POL	0	25	29	33	47	32	19	30	19
Portugal	PRT	0	41	42	40	39	30	30	37	35
Qatar	QAT	0	74	60	33	5	23	12	43	6
Saudi Arabia	SAU	0	45	16	24	31	67	87	45	82
Senegal	SEN	0	104	116	111	120	76	75	97	76
Serbia	SRB	0	51	59	77	83	73	79	67	80
Singapore	SGP	0	61	55	20	10	4	7	28	13
Sri Lanka	LKA	0	75	93	84	100	79	102	80	104
Sudan	SDN	0	81	66	91	107	127	129	100	129
Suriname	SUR	0	118	122	103	63	67	62	96	68
Tanzania	TZA	0	94	103	102	122	88	68	95	72
Thailand	THA	0	24	27	44	64	80	103	50	94
Trinidad and Tobago	TTO	0	95	99	72	41	58	58	75	63
Tunisia	TUN	0	77	85	78	92	75	104	77	105
Turkey	TUR	0	16	17	34	58	70	90	40	81
Turkmenistan	TKM	0	89	83	90	76	99	49	93	53
Uganda	UGA	0	112	117	112	126	103	110	109	111
Uruguay	URY	0	77	67	72	49	35	33	61	38
Uzbekistan	UZB	0	45	54	105	110	107	92	86	95
Venezuela, RB	VEN	0	29	15	43	57	118	114	63	113
Vietnam	VNM	0	26	23	67	94	73	54	55	56
Yemen, Rep.	YEM	0	99	104	97	112	124	128	107	128
Zimbabwe	ZWE	0	83	76	123	123	117	105	108	106

CHAPTER 5

Evaluating the cost, safety and proliferation risks of small floating nuclear reactors[4]

Abstract

It is hard to see how our energy system can be decarbonized if the world abandons nuclear power, but equally hard to introduce the technology in non-nuclear energy states. This is especially true in countries with limited technical, institutional, and regulatory capabilities, where safety and proliferation concerns are acute. Given the need to achieve serious emissions mitigation by mid-century, and the multi-decadal effort required to develop robust nuclear governance institutions, we must look to other models that might facilitate nuclear plant deployment while mitigating the technology's risks. One such deployment paradigm is the Build-Own-Operate-Return model.

Because returning small land-based reactors containing spent fuel is infeasible, we evaluate the cost, safety and proliferation risks of a system in which small modular reactors are manufactured in a factory, and then deployed to a customer nation on a floating platform. This floating SMR would be owned and operated by a single entity and returned unopened to the developed state for refueling. We developed a decision model that allows for a comparison of floating and land-based alternatives considering key IAEA plant-siting criteria. Abandoning on-site refueling is beneficial, and floating reactors built in a central facility can potentially reduce the risk of cost overruns and the consequences of accidents. However, if the floating platform must be built to military-grade specifications then the cost would be much higher than a land-based system. The analysis tool presented is flexible, and can assist planners in determining the scope of risks and uncertainty associated with different deployment options.

KEYWORDS: small modular reactor; floating nuclear plant; nuclear economics; nuclear proliferation; nuclear safety.

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[4] A version of this chapter has been published as: M. J. Ford, A. Abdulla, and M. G. Morgan. "Evaluating the cost, safety, and proliferation risks of small floating nuclear reactors," *Risk Analysis*, Jan 2017.

1. Introduction

The prospects for increased deployment of nuclear power plants (NPP) do not look good in OECD economies.(1) In the near-to-medium term, expansion in nuclear power generation is expected only in a few large or wealthy developing economies where electricity demand is growing rapidly.(2) And yet, today the technology is responsible for more than a tenth of the world's total electricity supply and remains one of only two proven, low-carbon sources of base-load power that can replace fossil fuels.[5] It is difficult to see how we can decarbonize the world's energy supply while simultaneously phasing out nuclear power. Indeed, many decarbonization studies assume the existence of a portfolio of reliable low-carbon options that include nuclear power, carbon capture and sequestration, and biomass plants.(2,4) Of these, only nuclear has previously been deployed at scale.

Nuclear power has its risks, however, and radically expanding its use in emerging nuclear energy states poses challenges for the institutions responsible for governing the technology. Developing nations contemplating their first nuclear plants face a multi-decadal undertaking, one that involves capacity building and intense internal and external scrutiny. If the world is to avoid the most catastrophic impacts of global warming, the bulk of our mitigation efforts must take place in the next several decades.(5,6) If its present design, licensing, construction, and deployment paradigms remain unchanged, it will be difficult or impossible for nuclear power to play more than a small role in the move towards a decarbonized energy system. Existing light water reactor designs, even Generation III+ variants, carry with them a high potential for cost overrun due to long development times, high long-lived radioactive waste generation and limited potential for the gains in plant efficiency which could lead to better economic competitiveness. Some advanced designs, such as molten salt or high-temperature gas cooled reactors, could mitigate many of these shortcomings; but design and development of these alternatives, while it has recently generated significant interest, has not led to a clear path for near-

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[5] The other is geothermal.

term deployment. Given the short timeframe required for successful mitigation, advanced nuclear designs are unlikely to be deployed at scale before mid-century.

One of the few remaining alternatives to retaining nuclear as part of the solution is a radical change in the deployment paradigm for reactors based on light water designs that may mitigate some of the historical shortfalls. This paper explores such a change, which involves an advanced supplier nation building, owning, and operating a fleet of small modular nuclear reactors (SMRs). These SMRs would be sited on offshore platforms, and their power transmitted to host nations via undersea power cables. Once their fuel is spent, they would be returned to a centralized facility for refueling and waste processing. These floating small modular reactors (fSMRs) might mitigate some of the risks associated with land-based reactors, enhancing safety and economic viability, while the build-own-operate-return (BOOR) model should help to reduce the material proliferation risks.

2. A New Model of Nuclear Power Plant Deployment

Small modular nuclear reactors (SMR)—which have a power output of less than 300 Megawatts-electric (MW_e)(6)—have been touted for the past decade as an option for communities in remote locations,**(Error! Reference source not found.)** for developing nations keen on meeting their growing energy demands using low-carbon sources(7) and even for replacing aging coal-fired energy infrastructure in the U.S.(10) Work to-date has focused on the potential advantages of using modular construction processes in the assembly of major plant components. It is argued that factory-based manufacturing will allow for better cost and quality control, ultimately lowering the risk of cost overrun, something that has plagued nuclear power plant (NPP) development in the past.(11) Some analysts even raise the possibility of cost reduction through technological learning, should the volume of plant orders be sufficient.(10)

The offshore deployment of NPPs is not a new concept.(12) In the U.S., one company worked through the 1970s to gain approval for the construction of eight floating Gigawatt-scale NPPs,[6] the first few of which were to be located off the coast of New Jersey.(13) More recent proposals by DCNS in France,(14) the Korea Advanced Institute of

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[6] The company, Offshore Power Systems, was a joint venture between Newport News Shipbuilding and Westinghouse.

Science and Engineering(15) and the Massachusetts Institute of Technology (MIT)(16) have advocated the development of floating nuclear plants of various designs, mainly to circumvent siting restrictions on land, as well as negative public attitudes to nuclear power.

Even if nations can afford to opt for an SMR as a carbon-free base load alternative, there are formidable regulatory and institutional hurdles that must be addressed, both immediately and in the long-term.(16) Relying on nuclear power demands virtually perpetual safety, security and waste management commitments on the part of host nations.(17) The indigenous development of these institutions requires a multi-decadal undertaking, and importing the necessary human capital is impossible for all but the richest states (the United Arab Emirates began its program less than ten years ago, and expects to commission its first reactor – which is on time and on budget – in 2017).(19) Compounding the problem is the fact that proposed deployment strategies design-out innovations that might address the safety, security and waste implications of nuclear power, on the assumption that regulators will not approve significant deviations from current practice. This strategy is misguided since novel deployment paradigms can reduce the economic, safety and security risks associated with NPP deployment.

One such paradigm, appropriate especially for emerging nuclear energy states that cannot afford the significant effort required to develop robust institutional oversight, is the BOOR model, which sees fueled modules deployed to customer nations, where they remain in operation until end of core life, at which point they are safely returned to centralized, supervised facilities for refueling and waste handling.(16) However, reactor designers from the U.S., China, India, Korea and Russia, with whom we have conferred, argue that, for the foreseeable future, shipping a fully fueled light water reactor to and from a land based location presents technical and safety issues that are likely to make costs prohibitive for a developing nation.

We have constructed an assessment model in the Analytica software package to compare the economic, safety and security risks of a land-based SMR with a floating SMR (fSMR) that closely adheres to the BOOR model. We took the International Atomic Energy Agency’s (IAEA) Siting Criteria as our starting point.(20) These, along with the IAEA’s specific safety guides,(21) are used in determining the suitability of new sites for

NPP deployment. The complete list of criteria is shown in Table A1 in Appendix A. We focused on criteria associated with the nuclear power plant parameter envelope, as well as the engineering and cost factors, which restricted our analysis to criteria that are different by nature of the two deployment options.

3. Evaluating offshore plants that adhere to the BOOR model.

Building an fSMR plant that adheres to the BOOR model has several advantages related to material control, proliferation risk and operational risk. **(1)** The entire deployment process can be modularized: historically, land-based NPP construction—much unlike shipbuilding—was so site-specific that little to no technological learning occurred over multiple installations. Standardization of land site development has always been the goal. The French nuclear program has come closest to achieving this but with only limited success.(21) With a floating model, construction of plant components and many site-specific considerations could be standardized, exploiting learning economies and limiting the risk of cost overruns in the process. Depending on water depth, timelines for development could potentially be shorter and should cause less disruption, since they would not entail the assembly of myriad complex plant components in a specific order and on-site. As noted by the IAEA, the predominant risk factor affecting the construction timeline of new land-based plants is civil and structural work, such as excavation, tsunami protection, seismic stabilization, and foundation development.(23) These activities lead to delays, which are responsible for a significant proportion of the cost overrun in a new development project by leaving capital and expensive labor idle.(23) **(2)** Internationalizing the nuclear fuel cycle: over the years, there have been many calls for improved international management and supervision of the nuclear fuel cycle, mainly in order to limit proliferation risk.(24) The reactor system we evaluate here, which adheres to the BOOR model, transforms nations interested in nuclear power into contracting nations. The responsibilities associated with refueling and waste handling are managed completely outside their purview, eliminating cost and risk drivers that might overwhelm inadequate institutions, and reducing the risk of material diversion. Nuclear fuel and waste would be managed in a nuclear capable state under stringent material control and accounting practices, reducing the risk of proliferation and focusing IAEA resources into monitoring fewer sites. **(3)** Increased energy delivery: with this model, the vendor can deliver power at a high (90%) capacity factor (CF) and, if a substitute barge is provided as a replacement for one that is at the end of its core life, the capacity factor will exceed that of typical Gigawatt-scale reactors, eliminating the need for alternative generating capacity in the process. The increase in CF results from elimination of downtime during refueling which is typically 4-5% of the ~10% total downtime for nuclear plants. Increased CF can be seen in the history of existing plants as refueling periods have shrunk leading to increasing overall CF for U.S. plants.[7] **(4)** Seismic and tsunami risk mitigation: if sited in waters of sufficient depth ($\gtrsim$100m), the risk to this platform from seismic or tsunami damage would be minimized, and the plant would not face difficulties in dealing with sea level rise.(25) **(5)** Accident consequence mitigation: siting plants offshore limits the consequences of potential radionuclide releases, as detailed in section 5. **(6)** More limited span of control: plant security is enhanced by the challenging nature of a waterborne approach and the narrower defense perimeter. Moreover, existing anti-swimmer systems, coupled with robust sensing systems under development, can yield a well-protected platform.

Offshore siting also has disadvantages. We discuss the cost of transmission and the different security risk profile in section 5, but other disadvantages exist. **(1)** Extreme weather impacts: operating in a marine environment during extreme weather events can be challenging. However, unlike proposals for siting large reactors offshore, our fSMR BOOR design does not involve refueling on location. Hence, there is no need for on-site heavy lift capability. In our design, operations that require significant maintenance—not to mention refueling—will be conducted in a secure dry dock. **(2)** Long-term maintenance: platform and component corrosion will become a life-cycle maintenance concern, and must be addressed in any offshore platform proposal. Cathodic protection systems, which are systems designed to prevent corrosion of metal components in hull and seawater systems, would be necessary (typical in most marine platforms), and periodic docking will be required for any barge-based plant like ours. **(3)** Logistics and staffing: a model akin to that used by deep-water oil platforms will be required to manage daily operations and staff the plant. Shore node to ocean terminal logistics infrastructure

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[7] For statistics on plant refueling outages and capacity factor, see http://www.nei.org/Knowledge-Center/Nuclear-Statistics/US-Nuclear-Power-Plants/US-Nuclear-Refueling-Outage-Days

will need to be established at each new site, and the unique environment will entail a potentially higher salary structure than that followed by land-based sites. **(4)** Risk of ocean releases: a clear concern in the event of an accident is the contamination of the ocean environment.(26) The smaller core load and lower core damage frequency (CDF) expected for SMRs reduces the risk when compared to large reactors, and the possibility that the barge could be towed to deep water if an accident begins could also mitigate contamination risks. Beyond the potential for radionuclide contamination of a coastal biota habitat, an accident could complicate return of the damaged reactor to vendor nations. **(5)** Licensing and regulation: this is potentially one of the most challenging issues. An offshore mobile platform, if positioned farther than 12 nautical miles (nm) from land, will pose international legal and regulatory challenges. Aside from the jurisdictional questions associated with regulatory oversight, deployment may necessitate more complex liability regimes to deal with transportation, emergency response in international waters and long-term security and proliferation resistance in both host and vendor nations. Some similar issues have been partly addressed by icebreakers and naval ships that are powered by nuclear reactors.

Regarding the BOOR model itself, there are clearly regulatory, liability and contracting issues associated with this model that may impact the specific application, cost, and viability for each host/vendor combination. Some wealthy but heretofore non-nuclear states may opt for a model that includes an ownership stake in the plant but relies on an external vendor to build, operate and then take custody of the plant at end of life. Some elements of such agreements have already been successfully negotiated between host/vendor partners: the Emirates Nuclear Energy Corporation signed an Engineering, Procurement, Construction, and Operation contract with its vendor, for example. Additionally, international development agencies could conceivably support the construction and operation of an fSMR in an emerging nation as a way to spur economic growth. It is not the intent of this manuscript to explore those more detailed issues related to the business model, but clearly, these will need treatment for any real world implementation.

4. Method

We used our Analytica model to investigate the relative cost of onshore and offshore siting, and to assess three key risks that would impact a decision to pursue either land-based or floating options. First, we analyzed how the two compare in terms of overnight cost and risk of cost growth, and the relative costs and risks of decommissioning, material and transmission. Second, we explored whether an fSMR mitigates risk in the Emergency Planning Zone (EPZ), and also considered the potential impacts of a marine accident. Third, we calculated the potential "water opportunity benefit" associated with a floating deployment method for host nations that have a limited water resource and face a high and growing demand for needs such as drinking water or irrigation. We used cost data gathered from a variety of literature sources on shipbuilding, nuclear development and decommissioning, transmission cost, material cost, and water withdrawal. Finally, we examined the proliferation advantages and disadvantages of an fSMR that adheres to the BOOR model. The proliferation question, due to its more speculative nature, was assessed qualitatively.

A few assumptions must be noted: though there are multiple potential designs, the floating plant model we describe here consists of a sea-based staging and electrical distribution platform (Figure 5-1), with the reactor plants housed within articulated, ballastable barges that would be rigidly moored to the staging platform. First, this design is faithful to the BOOR model and potentially simplifies construction, refueling, and maintenance. Second, it permits the use of ship and oil platform construction costs as analogs for floating SMR development. Third, the barge design is flexible enough to be used in other siting applications (e.g., pier-side operations in the arctic), expanding the set of potential customers. As for the land-based SMR, for this initial analysis, we assumed the site under investigation would contain one integral light water reactor, making it essentially a small light water reactor site. If an SMR could be designed that could be safely transported fully fueled to and from its use location, then a land-based BOOR deployment paradigm would be feasible. However, as noted above, most reactor design experts with whom we have conferred indicated that the shipment of either a fully fueled or spent light water reactor module to/from a developing world site would be a mammoth technical, economic, and institutional undertaking and with present designs is probably not feasible. As a result, a BOOR land site model was not included as a viable alternative to the floating option. Should advanced non light water reactors be developed, this option may well become possible in the future. As noted earlier, contracting vendors to operate the plants they build is possible, as experience in the Emirates shows. Regardless of land deployment paradigm (and as we will discuss in later sections) if a reactor is sited on the land of a sovereign state, it would be more easily accessed by state or other actors. If it is refueled on site, the same would be true of any spent fuel.

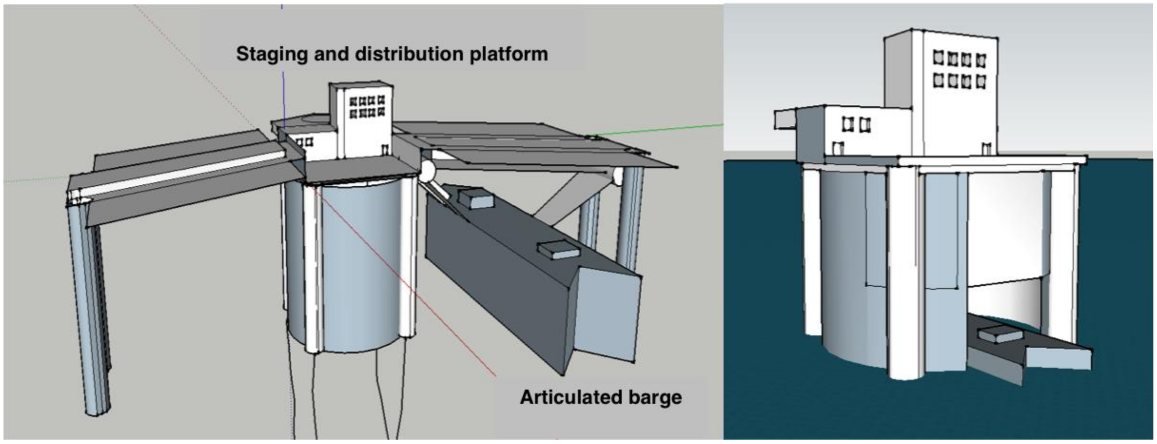

Figure 5-1. Two examples of our notional floating SMR platform, one that allows for multi-module deployment (left), and one that docks with a single articulated barge at a time (right).

We draw our land-based SMR construction cost data from the literature that incorporates some of the cost benefits potentially inherent in land-based SMR deployment. Should grid capacity require more than a single SMR, scaling of both siting options to incorporate multiple reactors is certainly feasible but is not explored here. Reactor and turbine components are assumed to be the same for both options. Therefore, the comparison of construction costs for land and floating sites focuses on differences in engineering, procurement and construction, as well as transmission yard, cooling system and installation costs. All other equipment costs and owner's costs are excluded from the comparison on the grounds that they would be identical. This includes refueling costs, which would be done every 24-30 months on location for a land-based site but would be done in a shipyard for the fSMR. Cooling water costs are only considered for the land site since the floating platform is designed for cooling with ocean water. Our model allows us to estimate the water opportunity “benefit” that accrues when an fSMR option is compared to a competing land site that would use freshwater cooling due, for example, to limited coastal property availability, concerns with urban encroachment, or risks from climate change and extreme events. A 2010 study examining the risk to coastal energy infrastructure in California indicated that there were potentially 30 power plants in the state—with a total generating capacity of over 10K MW_e—at risk of damage from a 100-year flood if a 1.4M increase in sea levels occurs due to climate change.(27) More recently, a 2014 study in Europe by Brown *et al.* indicates that as many as 71 nuclear power plants—37% of the European coastal total—may be at risk to flooding and damage related to sea level rise and extreme events.(28) Of course, some nations may still choose to develop a land-based SMR on a coastal site in which case; this benefit would not be applicable. Note that while there would technically be no additional “cost” for cooling a land-based plant from freshwater sources, other than development of the appropriate piping and pumping systems, there is an opportunity cost for urban communities due to the land site’s significant water withdrawals, not to mention other concerns, including thermal pollution of smaller waterways.

As shown in Figure 5-2, and as detailed further in Appendix B, our Analytica model consists of three major modules, one dedicated to the floating plant’s parameters, another to the land-based plant’s parameters, and a third that handles input/output. Each of the first two modules contains sub-modules dedicated to the costs under investigation: construction, emergency planning zone, decommissioning, transmission and materials. Additionally, the land-based plant has a sub-module dedicated to the opportunity cost of using freshwater for cooling, while the floating module contains an assessment of the impacts of a marine accident. Using the input/output page, an analyst can choose parameter values for each of the model’s variables. In the results reported here, probability distributions are used to allow influence assessment of key parameters, though the modelers can change the type of parameter or distribution to suit requirements. As it stands, the model provides a differential comparison of the two siting methods, which is presented as a “floating value minus land value.” We adopted this approach in order to develop cumulative distribution functions (CDF) that allowed assessment of the probability of differential (as opposed to absolute) costs based on variable assumptions. Table 5-1 provides a summary of key nodes, values, and sources for the floating reactor plant, and Table 5-2 does the same for the land-based plant. Throughout, costs are reported in $\$_{US}x10^6$ (2012). For simulations involving chance nodes, 10,000 iterations were conducted. Appendix B contains a full description of the model, including a complete breakdown of model nodes and key calculations.

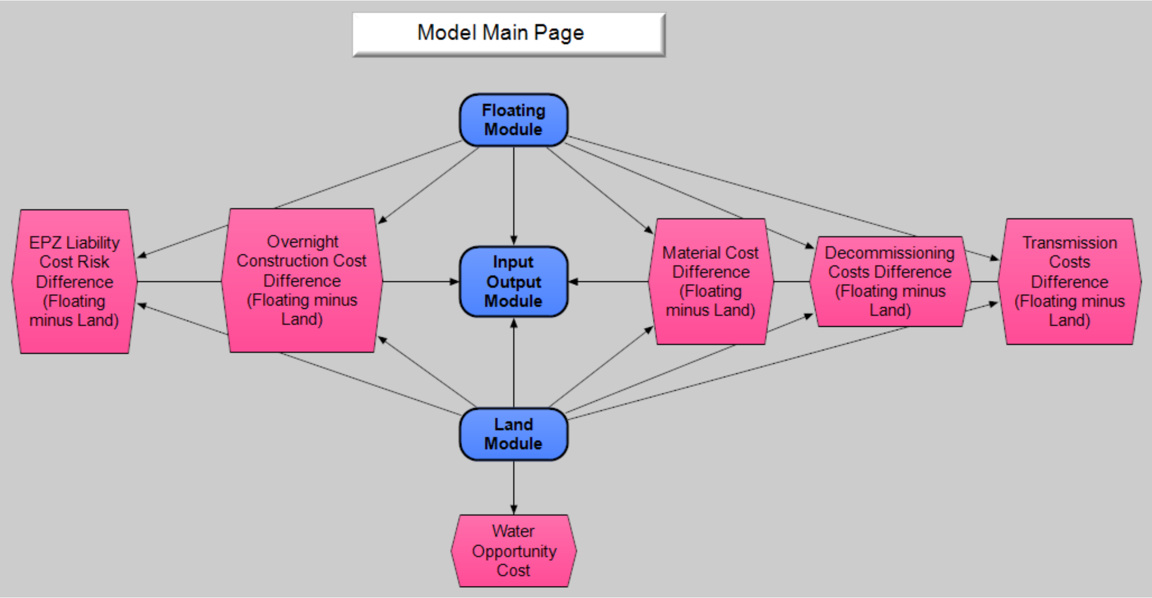

Figure 5-2. An overview of the main page of our Analytica model, which has three major modules: one investigates the land-based SMR, another investigates the floating SMR, and a third allows the modeler to modify assumptions and data to evaluate a specific scenario. Appendix B contains a full description of the model.

Table 5-1. An overview of the main variables in our Analytica model's floating module. Consult Appendix B for model description.

		Module/Submodule	Range	Units	Distribution	Sources
Floating	Construction	Hull form size - com	50,000-70,000	DWT	Uniform	Estimated mass of plant and ballast (deadweight).(30)
		Hull form size - mil	10,000–20,000	T	Uniform	USN Nuclear Guided Missile Cruiser;(31) USN Amphibious Ships.(31)
		Hull prices – commercial	300–750	$/DWT	Triangular	UN Review of Maritime Transport (32), using 3 ship types ranging from 50,000T to 300,000T as bounding cost factors.
		Hull prices – military (USN and ROW)	30,000 - 75,000 10,000 – 25,000	$/T	Truncated Normal	CRS;(33,34) USN Budget Justification documents;(35) Low-end reflects non-U.S. costs of construction.(35)
		Hull – overrun	0–30	%	Uniform	Assumed overrun to account for unique nature of the hull form.
		Staging and distribution (S&D) platform prices	300–750	$M	Uniform	Spar rig costs expanded to account for unique structural configurations and more robust construction standards.(37,38)
		S&D platform – overrun	0–15	%	Uniform	Assumed overrun to account for unique nature of the platform.
		Learning curve	0.9–1	–	Uniform	USN Virginia Class: fixed-price, multi-unit contracting.(39)
		Security barrier unit cost	$5\times10^{-4} – 7\times10^{-3}$	$M/m	Selectable	Estimate provided by Harbor Offshore Barriers.(40)
		Security barrier radius	200–1,000	m	Selectable	Max range 1000m used as a bounding value.
	Trans.	Range	1–10	mi	Uniform	Max range 10mi for consistency with EPZ value; Min range 1mi.
		Cost per mile	1–10	$M/mi	Truncated Normal	Neptune Systems costs;(411,41) Siemens;(43) NorNed link costs;(43) Assumption of minimum cost of $1M/mi.
	Decomm.	Decomm. cost	85	$M	-	Code of Federal Regulations.(45) (value based on plant size)
		Energy cost index	2.704	–	Fixed	2012 cost index.(46)
		Labor cost factor	1.5–3	–	Selectable	NRC NUREG-1307.(46)
		Burial cost factor	6–32	–	Selectable	NRC NUREG-1307.(46)
		Plant size	10,000–300,000	kW_e	Selectable	225,000kW_e used as representative size for an SMR.
		Mil. decomm. cost factor	0.0004-0.001	$M/$kW_e$	Fixed	USN Budget Docs for CVN65 and submarine inactivations.(47-49)
	Mat.	Staging rig weight	20,000–30,000	T	Uniform	Kaiser.(37,38)
		Hull form size	10,000–20,000	T	Uniform	USN Nuclear Guided Missile Cruiser.(31)
		Cost of steel	250–800	$/T	Uniform	Steel on the Net;(50) MEPS;(51) and Steel Benchmarker.(52)
	EPZ	Distance from coast	1–10	mi	Uniform	Max range 10mi for consistency with EPZ value; Min range 1mi.
		Population density	10–200	pop/km^2	Uniform	NRC Guidance Manual 4.7.(53)
		Economic Impact Factor	13-400	$/pop/km^2	Triangular	Sovacool;(53) TEPCO;(54) Vasquez,(56) IAEA.(57)
		EPZ pathway distance	10 or 50	mi	Selectable	NRC EPZ planning ranges.(57)

Units: DWT = deadweight ton; T = ton; m = meter; mi = mile; kW_e = kilowatt-electric; pop = population; km = kilometer.

Abbrv: USN = U.S. Navy; NPP = nuclear power plant; ROW = rest of world; CRS = Congressional Research Service; EPZ = Emergency Planning Zone; NRC = U.S. Nuclear Regulatory Commission; TEPCO = Tokyo Electric Power Company; IAEA = International Atomic Energy Agency.

Table 5-2. An overview of the main variables in our Analytica model's land-based module. Consult Appendix B for model description.

		Module/Submodule	Range	Units	Distribution	Sources
Land	**Const.**	Overnight costs	3000-7200	$/kWe	Truncated Normal	Abdulla et al.;(59) Rothwell;(60) U.S. EIA.(61)
		Site constr. cost factor	0.635	_	Fixed	Black and Veatch.(62)
	Trans.	Range	0–10	mi	Uniform	Max range 10mi for consistency with EPZ value.
		Cost per mile	0.1–2	$M/mi	Truncated Normal	Greenwell;(63) Edison Electric Institute;(64) PG&E;(65) Wisconsin PU;(66) National Council on Electricity Policy;(66) Assumption of minimum cost of $1M/mi.
	Decmm.	Decommissioning cost	85	$M	-	Code of Federal Regulations.(46) (value based on plant size)
		Energy cost index	2.704	–	Fixed	2012 cost index.(46)
		Labor cost factor	1.5–3	–	Selectable	NRC NUREG-1307.(46)
		Burial cost factor	6–32	–	Selectable	NRC NUREG-1307.(46)
		Plant size	10,000–300,000	kW$_e$	Selectable	225,000kW$_e$ used as representative size for an SMR.
	Mat.	Cost of steel	250–800	$/T	Uniform	Steel on the Net;(50) MEPS;(51) and Steel Benchmarker.(52)
		Mass of steel	See model		Selectable	UC Berkeley;(68) ORNL.(69,70)
		Cost of concrete	100-160	$\$/\text{m}^3$	Uniform	ENR Construction;(71) CA DOT cost estimates.(72)
		Mass of concrete	See model		Selectable	UC Berkeley;(68) ORNL.(70)
	EPZ	Distance from coast	1–10	mi	Uniform	Max range 10mi for consistency with EPZ value; Min range 1mi.
		Population density	10–200	pop/km^2	Uniform	NRC Guidance Manual 4.7.(53)
		Economic impact factor	13-400	$\$/\text{pop/km}^2$	Triangular	Sovacool;(53) TEPCO;(54) Vasquez,(56) IAEA.(57)
		EPZ pathway distance	10 or 50	mi	Selectable	NRC EPZ planning ranges.(57)
	Water	Water volume	1-30	HCF	Triangular	NREL;(73) NETL;(74) MIT;(75) NEI;(76) WNA.(77)
		Water cost	3-10	$/HCF	Triangular	San Diego Water District;(78) Seattle;(79) comparative overseas rates.(80)

Units: kWe = kilowatt-electric; mi = mile; T = ton; m = meter; pop = population; km = kilometer; HCF = hundred cubic feet.

Abbrv: EPZ = Emergency Planning Zone; NRC = Nuclear Regulatory Commission; ORNL = Oak Ridge Natl. Lab; TEPCO = Tokyo Electric Power Company; IAEA = International Atomic Energy Agency; NREL = Natl. Renewable Energy Lab.; NETL = Natl. Energy Tech. Lab.; NEI = Nuclear Energy Institute; WNA = World Nuclear Association.

5. Results and Discussion.

5.1. Project cost and risk of cost growth

Our results indicate that deploying an fSMR that adheres to the BOOR vision has a number of advantages when compared to a land-based equivalent. The first question we asked in section 4 above was whether the floating option could achieve better control of cost than the land-based option. Using the values assumed in Tables 5-1 and 5-2, there is a greater than 80% probability that the cost of the floating option will be lower than the land-based reactor's if *commercial* shipbuilding costs apply. A 50 to 70 thousand deadweight-ton double hull barge, with a staging platform, a uniformly distributed 0-10% learning rate, and a security barrier would have a median cost of ~$620M (10th and 90th percentiles of $400M and $770M, respectively). Assuming no cost overrun, the land-based site, with a median specific cost of approximately \$5300/kW$_e$,(59) would have a median cost of ~$760M (10th and 90th percentiles of $660M and $850M, respectively). As mentioned in the previous section, these costs are for the site and platform development only, and in both cases do not include reactor or turbine plant equipment, which we conservatively assume to be comparable across the two deployment options when considering "Nth of a Kind" development. In fact, costs of shipment/placement for plant components to host nations would most certainly lead to higher cost when compared with the development of fSMRs in a centralized facility. Figure 5-3 shows the cumulative distribution functions both for the two options (5-3a) and for the difference between them (5-3b). An importance analysis indicates that the cost of the staging platform is the dominant cost factor in the floating plant.

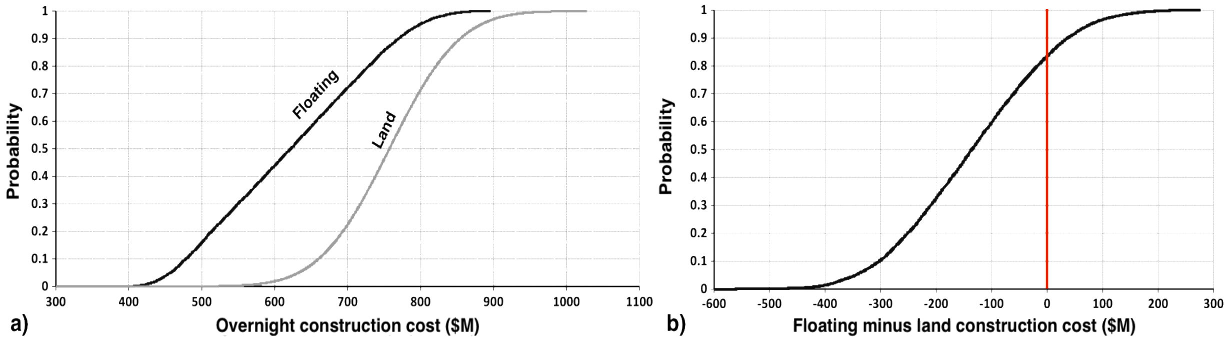

Figure 5-3. Cumulative distribution functions **a)** comparing the construction costs of the floating and land-based SMR deployment options using cost data that comply with commercial shipbuilding specifications, and **b)** showing the difference between the two options. Under this scenario, there is a >0.8 probability that the floating option will be cheaper than the land-based option.

At the other extreme, if *military* shipbuilding costs are assumed, the picture changes dramatically (Figure 5-4). Our cost estimates consider vessels in the U.S. Navy's surface fleet, with nuclear aircraft carriers, nuclear cruisers, and amphibious ships representing the bounds of our analysis. These vessels are built with material, reinforcement, weld inspections, etc. that all meet MILSPEC specifications for combat vessels.

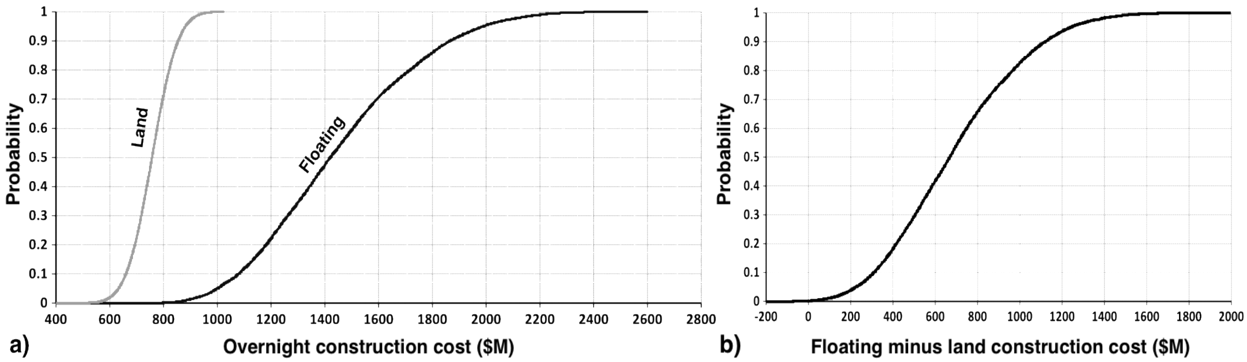

Figure 5-4. Cumulative distribution functions **a)** comparing the construction costs of the floating and land-based SMR deployment options using cost data that comply with military shipbuilding specifications, and **b)** showing the difference between the two options. Under this scenario, the construction cost of the land option consistently dominates that of the floating option.

When these costs are applied, the land-based reactor dominates the floating option. Figure 5-5 shows that assumptions about hull form size and cost have the most influence on plant cost.

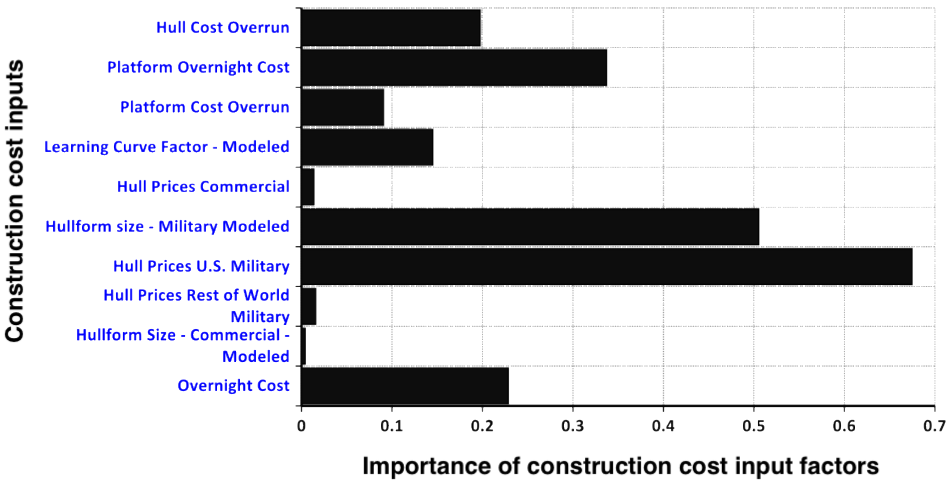

Figure 5-5. As our importance analysis shows, the size and price of the hull form are the factors of greatest consequence in our model when military constructions specifications are assumed.

Ship construction is robust worldwide, and a prior U.S. assessment suggested that military hulls could be built overseas for one-third of their U.S. cost.(81) In this case, the floating option's cost would be approximately equivalent to the land-based option, again assuming that the latter experiences no cost overrun. To model this in an alternative fashion, we examined international shipbuilding cost metrics which are based on Compensated Gross Tonnage (CGT), a measure of the gross tonnage of a vessel corrected to account for platform type, size and complexity. CGT calculations are spelled out by the Organization for Economic Development and Cooperation (OECD).(82) While CGT calculations do not cover military platforms, a 2005 assessment of global shipbuilding considered the CGT methodology for more complex naval platforms and noted that international shipbuilding productivity (measured in man-hours/CGT) is almost twice that of U.S. naval shipyards.(83) Additionally, labor costs in nations which conduct a predominant amount of commercial shipbuilding (e.g., South Korea, China) are lower.(84) These factors strongly indicate that the hullform could be built for far less when using non-U.S. shipbuilding factors. Using factors from the global shipbuilding study, we modeled potential barge costs considering CGT and a "Customer Factor" which varies from 1.06 to 1.18 to reflect the increased performance requirement that applies to a naval platform (and perhaps would apply to a floating nuclear power plant). When modeled using these factors, a CGT value of 25-30 would lead to costs that are equivalent to the mean land site cost of construction (nominally $750M). Note that a very simple commercial hullform has a CGT factor as low as 0.3 while the most complex naval platform, a nuclear submarine, can be as high as 80.(83) To highlight the impact of variation in world ship construction, the preeminent shipbuilding nation worldwide is South Korea, which recently announced the development of three new Aegis Destroyers at a unit cost of ~$934M.(85) The comparably sized military platform in the U.S. is an Arleigh Burke Class Destroyer, which is expected to cost ~$1.8B per platform, or almost twice that of the South Korean platform.(86)

Despite the very strong potential that the hull can be built for a reasonable cost on the international market, there is still a substantial construction cost risk with floating development. The cost benefit accrued to the floating option would quickly dissipate if delays or changing construction requirements lead to extended construction timelines. Even granting the much lower cost of building somewhere like South Korea, the greater requirements of building to military specifications still imply a cost in excess of $50,000 per ton (vs. $500-1000/ton for conventional commercial ship construction) when evaluating the cost of the Aegis destroyer example above. Ultimately, regulatory decisions have caused significant delay in past NPP developments, so well run shipyards and designs developed to the minutest details will be a key to maintaining cost control.(87) Our model indicates that barge costs likely need to remain below $16,000/ton (using a light displacement of 15 thousand tons) to remain competitive with land-based deployment. Using CGT methodology, the CGT factor would likely need to remain below 30. Staging and Distribution platform costs are assumed to mirror commercial spar type oil platform costs.

5.2. Decommissioning, transmission, and material costs

There are significant differences between the two options when it comes to decommissioning, transmission, and material costs as well. The (sparse) evidence that exists suggests that the same benefits that accrue to floating reactors during the construction phase (mainly the centralized construction location) accrue to them during the decommissioning phase. In the U.S. and elsewhere, decommissioning costs are controlled by regulation. While it is unlikely that an fSMR operation would be based in the U.S., for this model baseline costs were assumed to follow U.S. NRC NUREG–1307 and 10 CFR 50.75 decommissioning funding guidelines, which are based on plant size. Because we assume equivalent plants, the net cost difference is zero. Required funding levels in the U.S. for an SMR site of 225MW$_e$ vary depending on region, and can range from $300-700M. Remediating the site of a floating plant differs from land-based remediation. While there would certainly be site testing and some ocean floor remediation, it makes more sense to compare floating platform decommissioning to the disposal costs incurred by large naval nuclear platforms. The most recent example is the USS ENTERPRISE, which carried eight small modular reactors. Disposing of the ENTERPRISE's reactor compartment will cost roughly $750M,(49) which translates to less than $100M per plant. This was a larger decommissioning effort than a commercial SMR barge would be, and if regulatory changes were introduced for SMR decommissioning funds, they would benefit the floating option. The U.S. Navy budgets approximately $120M for the inactivation of a nuclear submarine,(47,49) and has completed them for less, averaging $41M ($FY12) per ship for 11 submarines inactivated from 1988-1990.(49) Costs for final disposition of floating variants of commercial reactors would likely be somewhat higher since naval plants are more compact and more readily buried but overall decommissioning costs will still have more in common with a naval model and should be examined to see if there are benefits with respect to decommissioning that accrue to a marine model. Another factor in new site development is proximity to existing power infrastructure. The added complexity of a marine siting application will necessitate higher transmission costs. Cost factors from Siemens, Pacific Gas and Electric, the Edison Electric Institute, and MIT indicate that marine cabling costs could exceed $3M per km, while land cabling is highly dependent on terrain, urban vs. rural siting and above vs. below ground installation.(63) With this in mind, costs for the floating application were approximated at a mean of $6M per mile, while land rates were varied around $500K per mile. Transmission distance was also varied for the two siting modes. Figure 5-6 shows the CDFs of both options. As expected, there is a 0.98 probability that transmission costs for floating sites will be higher, with a median difference between floating and land sites of about $26M. This cost is significant, and might conceivably become a factor in deciding between the two options, but it is dwarfed by the overnight cost.

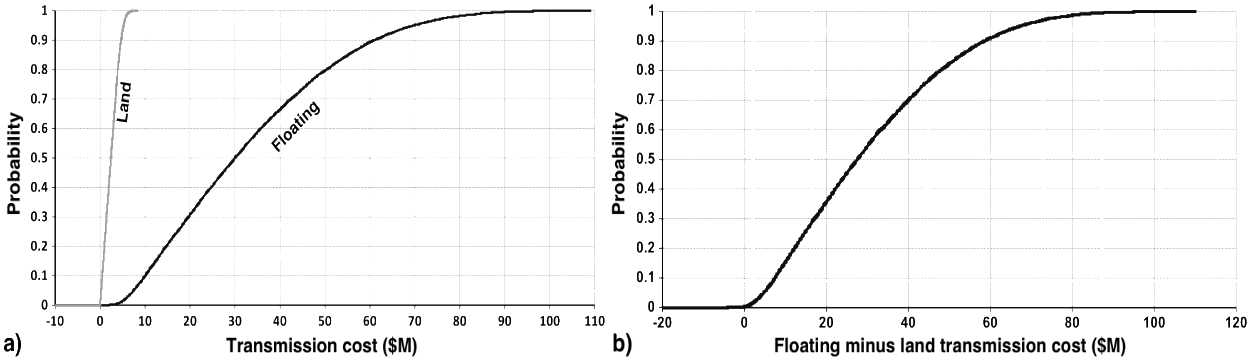

Figure 5-6. a) As expected, transmission costs heavily favor the land-based site, though **b)** the absolute value is small relative to the total investment.

A third potential risk driver is the cost of the materials since variability in commodities pricing affects proposed builds. To examine this, we compared the costs of concrete and steel in floating and land-based deployments. As shown in Figure 5-7, model results indicate that material costs are consistently higher for the floating plant, given the greater weight and higher cost per ton of steel, with a median cost of $21 million compared to the land-based site's median cost of <$5M. Again, in absolute terms, the cost of materials is a minor factor in comparisons between the two options and has less to do with acquiring raw materials than the on-time delivery of finished materials in a shipyard with high labor costs.

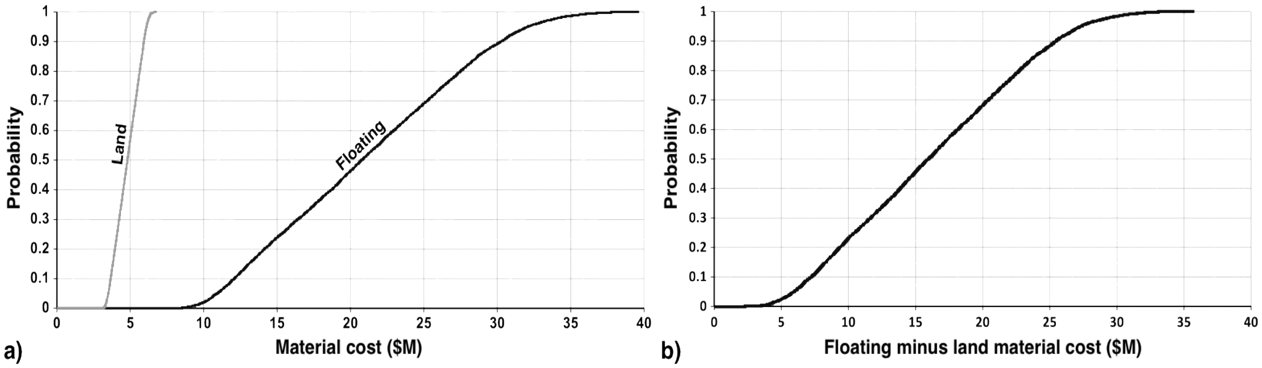

Figure 5-7. Cumulative distribution functions **a)** comparing the material costs of the floating and land-based options, and **b)** showing the difference between them. Concrete-intensive land-based plants dominate steel-intensive floating plants, given the greater cost of the latter; still, the cost of the materials is a very small part of the project total.

5.3. Accident Risks

5.3.1 Atmospheric release compensation and remediation risk

Nuclear reactors are required to maintain an Emergency Planning Zone or EPZ.[8] Analyzing EPZ risk requires a comprehensive site-specific evaluation, including extensive risk analyses that incorporate population density, demographic structure, weather patterns, seismic and other natural hazards, core load for the specific design, probabilistic risk assessment, and myriad of other factors. Because our assessment assumes comparable plants both on and offshore, the safety features inherent to the chosen design would accrue to both options. A comprehensive risk assessment for the floating variant would likely fair better for seismic/tsunami risk, given the nature of the deployment method. The location in what is essentially an infinite heat sink would also weigh in favor of the floating option. Of course, risks for the onshore site will depend on location and nearby population and facilities. Risks for the offshore location include collision, flooding, stability impacts on flow characteristics and emergency response availability. Because both are site specific, we do not include them in this first order comparison.

Our model first provides a stylized order of magnitude estimate of the implications for EPZ risks as a plant’s distance from shoreline increases. Our results, shown in Figure 5-8, suggest that the overall risk of compensation and remediation liability in the event of an accident is lower for the floating plant, given the reduced risk of plume exposure or ingestion. We assume a circular affected area of 10 or 50-mi diameter that begins at the coast and moves inland (land-based plant) or offshore (sea-based plant), modeled as a uniform distribution. A comparable population density distribution is used for the two modules, and a distribution of liability costs is developed using values from Three Mile Island (minimum),(53) Fukushima (mode)(54) and Chernobyl (maximum).(56,57) As modeled, the fSMR platform would incur lower compensation and remediation costs 90% of the time in the event of an accident. The results are not quite as dramatic for the 50 mile ingestion pathway, but the floating site option would still have an ~60% probability of lower liability costs.

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[8] For details on EPZs see: http://www.nrc.gov/about-nrc/emerg-preparedness/about-emerg-preparedness/planning-zones.html

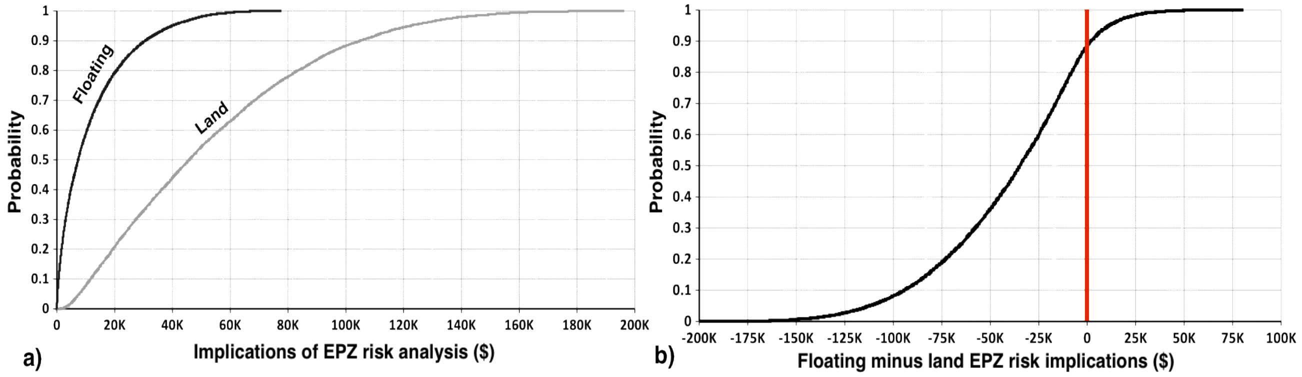

Figure 5-8. Cumulative distribution functions **a)** comparing the EPZ accident risk implications for the floating and land-based options, and **b)** showing the difference between them. Our results suggest that the floating option has a >90% likelihood of reducing the implications of an accident, given the smaller affected population.

The intent of the model is not to imply a deterministic exposure risk value for either siting method, but to point out the fact that the risk is more likely to be minimized in a floating plant due to its distance from population centers. In Figure 5-9, we show an importance analysis of the factors involved in the analysis and makes the point just mentioned more obvious.

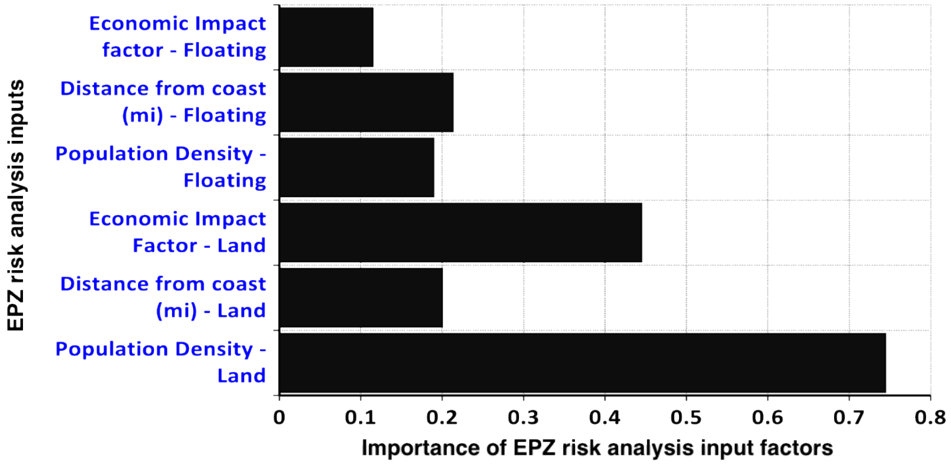

Figure 5-9. From our importance analysis, it is clear that population density and the costs of remediation and compensation are the most consequential risk drivers for the land-based option. However, the ability to determine (or even adjust) distance from population centers affords the floating option greater flexibility in managing risk.

Clearly, we can postulate regional, weather, or site conditions where this is not true, which necessitates a careful site-specific assessment of the consequences of NPP deployment, as required by regulation for any new plant. Additionally, we assume that remediation costs would be similar for all sites, but accidents are not uniformly severe, so impacts and costs will likely be lower for an fSMR if hull integrity is maintained and environmental release is minimized. The platform can be moved farther out to sea in the early stages of an accident as part of an emergency response plan, and this unique trait can mitigate the affected population's exposure risk, though it might carry international legal ramifications. The option to move the platform would require further policy and liability assessment to ensure that the potential consequences have been considered—and emergency action plans are agreed upon—before first-of-a-kind deployment.

5.3.2 Marine accident consequence

The long-term consequences of environmental release from a reactor based on land have been well analyzed across a range of accident sizes, from Three Mile Island to Fukushima.(53-57) Accident remediation is complex, time-consuming, and expensive. While the probability of an accident at an SMR is very low, if significant releases do occur—as with Chernobyl and Fukushima—long-lived "no go" zones must be established, which carry with them environmental, health, safety, and economic impacts.(89) Given Fukushima's scale, some have even advocated delaying that affected region's cleanup for 3-10 years to mitigate cost and exposure risk.(90)

In addition to the literature on land-based accidents, there is a robust literature on past marine releases, including submarine sinkings, release in marine environments from UK and French reprocessing plants and, more recently, from the marine release at Fukushima.(89-101) The overarching conclusion in this literature is that the long-term impact of marine release on marine biota and human food sources has been much lower than that found in large land based releases, although there remains uncertainty about the very long-term impacts on both aquatic as well as terrestrial biota from low-level radioactive contamination.

The most recent marine release example is Fukushima, where the magnitude of the total radionuclide release is still under review. Estimates have placed the marine release somewhere between 7-27 PBq for the key nuclide Cs-137(100) (note - some estimates are much lower(97) while some have placed it even higher(100,101)). I-131 releases were estimated at ~100-400 PBq. In the case of Fukushima, the marine release was predominantly from seawater used to cool the damaged units and spent fuel pools.(97,99) For land contamination, Cs-137 land deposition has been estimated at ~6 PBq with I-131 at ~74PBq.(97,100) A 2015 report from the Japanese Atomic Energy Agency indicates that it will be years before the areas surrounding Fukushima will be decontaminated to the point of habitability.(99) In contrast, though as much as 27 PBq of Cs-137 and 400 PBq of I-131 was released offshore, within two years the predominant number of biota samples taken off the Japanese coast reflected contamination that was less than established limits. After four years, no fish samples contained concentrations of radionuclides above established guidelines (100 Bq/kg).(102) It is true that seafood from the region has yet to be declared "safe for consumption," but this reflects the dominance of politics and public perception in every post-remediation decision that must be taken by the Japanese government.

Because our fSMR design assumes a smaller core load than that of Fukushima units 1-4, we incorporated a module in our model that scales the Fukushima findings (in percentage terms) to assess how a comparably sized release from an fSMR would compare. Note that for this type of significant release to occur, a multi-level failure of containment would have to precede the event or a non-filtered release would be required as part of casualty mitigation efforts. We estimated the time at which the level of fish contamination would reach "less than" established limits, comparing it to the four (4) years that were necessary for levels at Fukushima to drop below those limits. Of course, such an order of magnitude estimate only applies to this specific site since every potential fSMR site would have unique depth, current and weather patterns, not to mention potentially far different biota composition. To model the release from an fSMR, we calculated a core load for a 225 MW_e plant, assuming fuel parameters comparable to a standard GW-scale LWR. The values we used are included in Table 5-3. We assumed the highest estimate Cs-137 release of ~27 PBq and I-131 release of ~100 PBq and modeled the total release source term as a distribution from 80-130 PBq with modeled release as a percentage of the overall estimated core load of the four damaged reactors (attributing the majority of radioactivity content for the cores as Cs and I).[9] This result is an overestimate

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[9] The two key radionuclides chosen for this first order assessment (I-131 and Cs-137) were chosen because they have significant core concentration, have potential uptake in marine biota, have higher radioactivity

of core release (especially Cs-137) since some of the released radionuclides came from damaged spent fuel pools at the site.(97,99) We then calculated a decay rate for the contamination fish population would be exposed to, using data published by the Japan Fisheries Agency.(102) Were an fSMR to cause a release that is comparable in percentage terms to Fukushima, our results indicate that seafood would reach a contamination level "less than" established limits within ~2.7 years. The radionuclide inventory that would have to be released for this comparison to hold must, of course, be similar to Fukushima's. Figure 5-10 provides the cumulative distribution function for the parameters modeled. Given the more advanced safety features of SMRs, ocean basing with abundant cooling water, and multi-level containment, we believe this order of magnitude estimate to be an improbably serious worst case.

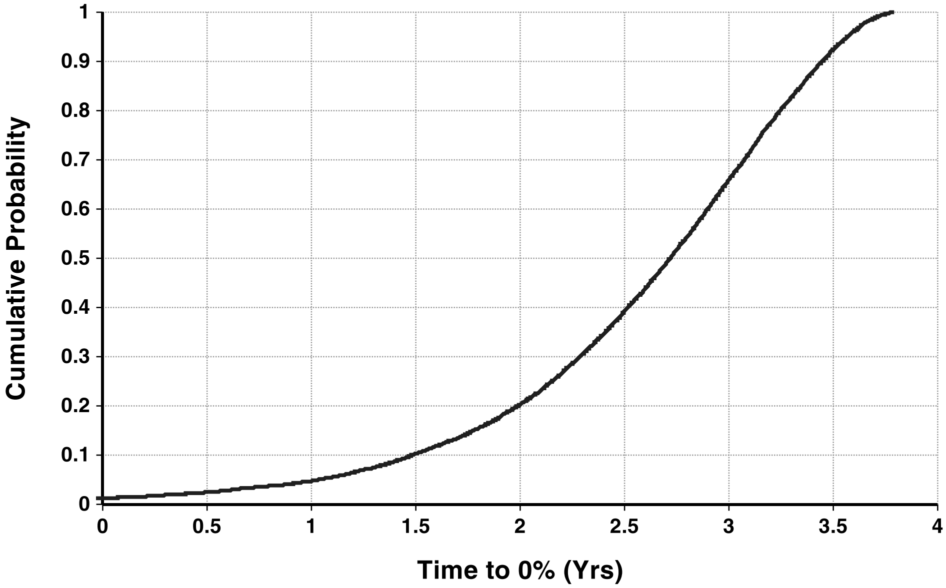

Figure 5-10. Our simulation of the impact of an accident with radionuclide release in a marine environment reflects nominally 2.7 years until contamination levels for fish in affected areas would sample at less than the established guidelines for radionuclide content. This estimate is specific only to Fukushima since the factors used reflect the unique currents and biota of that area. This is an improbable worst case for an fSMR but reflects an accident size that equates to the size of a Fukushima level release for the smaller fSMR.

Any environmental release has extremely negative consequences and, as has been well documented in the literature, the long-term impact of low-level radionuclides on the

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levels (Bq) and have longer half-lives (I-133 and I-135 have higher radioactivity levels (Bq) but short half-lives).

overall health of the local biosphere is not fully understood. As a result, any detailed siting analysis would need to attempt to minimize potential future impacts by placing the reactor outside of critical fishing grounds, just as land siting considers the long-term risk to population centers and the food supply. Should an accident occur, it is critical to consider which parties would be liable for post-disaster cleanup, not to mention where a damaged fSMR could be taken and made safe. For any vendor nation, accepting custody of spent fuel is a challenging technical and political feat in itself. Taking custody of a damaged plant would pose even larger obstacles. This is an issue that arises in different forms under a BOOR model for either a land or sea case.

Table 5-3. An overview of the variables in our Analytica model's Marine accident module. Consult Appendix B for model description.

		Node/Subnode	Range/Value	Units	Distribution	Sources
Marine Accident	**Time to 0%**	Capacity factor	0.86-0.92	%	Truncated Normal	U.S. EIA.(62)
		Annual mass UO2	20-30	T	Uniform	WNA.(103)
		Fukushima release	80-130K	TBq	Uniform	IAEA;(99) Burns;(97) Kobayashi;(100) JAEA.(101)
		Decay constant (λ)	-1.4	Yr^{-1}	Fixed	Japan Fisheries Agency.(102)
		Bq per ton	1E+11-1E+17	Bq	Uniform	Burns.(97)
		Fukushima core load	200-220	T	Uniform	Based on Fukushima 1-4 MW rating from TEPCO Accident Overview.(104)
		Accident release %	10-100	%	Uniform	Author modeling choice to reflect range of accident levels.

Units: T = ton; Bq = Bequerels; TBq = TeraBequerels.

Abbrv: TEPCO = Tokyo Electric Power Company; IAEA = International Atomic Energy Agency; WNA = World Nuclear Association; JAEA = Japan Atomic Energy Agency.

5.4. Water opportunity benefit

As we note above, if options being considered for land sites in a host nation require use of a freshwater source for cooling, then a water opportunity benefit should be included in the cost/benefit comparison. Based on the size of our plant and commercial water rates drawn from arid regions, such as southern California, as well as more typical areas, such as the U.S. Pacific northwest and international values from Germany and Norway, model results indicate that there would be an almost $12M per year "water opportunity benefit" when using ocean water for cooling instead of the freshwater sources that inland plants would exploit. Figure 5-11 provides the cumulative distribution function for this cost.

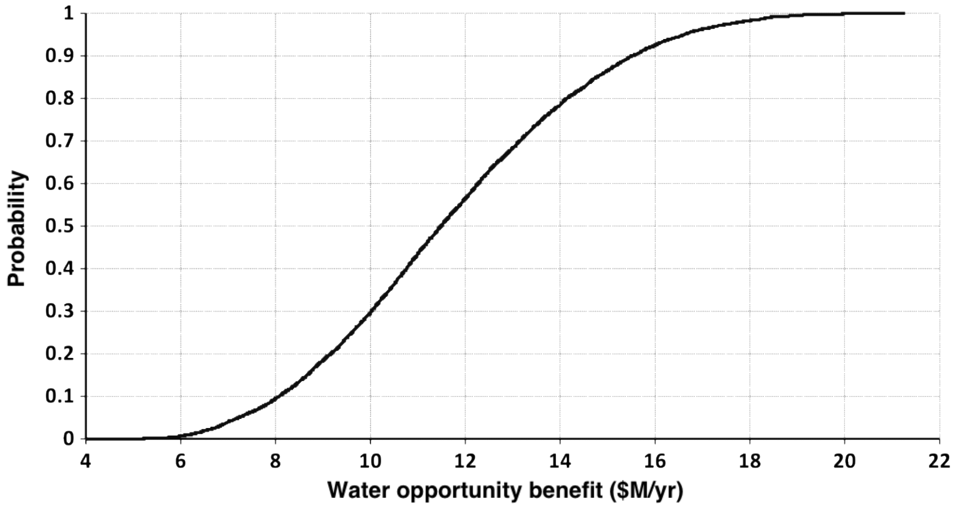

Figure 5-11. The annual water opportunity benefit associated with using ocean water for cooling, instead of the freshwater sources that an inland plant might utilize, is substantial. Cooling water availability is one of the main obstacles to siting large thermal generators and given concerns over freshwater scarcity; it is wise to ascribe a value to this benefit for generators that do not rely on freshwater for cooling.

Water opportunity costs will vary based on plant location and size, but it is clear that the floating option avoids exploitation of scarce freshwater resources, a factor that could become more important as climate changes. In one recent assessment of SMR siting options, cooling water availability was deemed the most critical determinant of site suitability in the U.S.,(88) and the same is probably true worldwide. Infrastructure planners concerned about conserving scarce water resources should evaluate incentives for new energy infrastructure that does not rely on freshwater withdrawal. Our finding suggests that a floating SMR could avoid the environmental impacts of inland energy infrastructure development. Not considered here are the floating plant's potential secondary process applications, such as water desalination for arid regions or impacts from thermal pollution.

5.5. Implications of floating SMRs on nuclear security

The proliferation risks associated with an fSMR that limits all handling of nuclear materials to a nuclear-capable state are lower for several reasons. First, it preempts the development of multiple national nuclear programs. Second, it eliminates the need for onsite refueling, reducing the risk of nuclear material being compromised. Third, it ensures robust material control and accounting practices are employed, by restricting fuel handling to centralized, secure facilities under international supervision. In the same vein, it renders unnecessary the spent fuel pool, which is a substantial cost and risk driver on any site.

From a physical security perspective, an fSMR sited well offshore and away from sea lanes would enhance physical security by reducing the size of the defended area. Floating platform security would likely maintain a defense in depth approach, similar to that used by international navies. The platform and areas surrounding it—nominally to 1000 yards—would be considered a "vital area." This area would be protected in our model by a barrier fence, which we have incorporated into the cost structure for fSMR overnight costs. The area from 1000 yards to approximately 5nm would be an Identification, Interrogation and Engagement Area. Finally, the distance to the horizon (nominally 12nm) would be a Surveillance Area, incorporating radar and visual systems. Defensive forces would have a greater ability and time to assess incoming unknown contacts when compared to a land site, both due to a greater field of view and also, for typical surface and subsurface approach options, a much slower possible rate of approach than for a typical land assault. Approaching the fSMR site would be more challenging, and doing so covertly would require highly trained forces. Additionally, the subsea location of the core would render any attempt to cause a release at the site more difficult. Fuel handling materials would not be available onboard. Staffing the platform would be the responsibility of the contracting vendor, limiting both the need for human capital development in host countries and, with proper vetting, the risk of insider threat. However, this reduced insider threat risk would also apply to a BOOR land site.

There are several potential disadvantages, too. Among them is the potential for unauthorized movement or hijacking. The nature of the platform would make it challenging for any group to move the entire structure covertly before intervention from security forces. From a physical security standpoint, the offshore location will make host nation threat response more challenging. This will, of course, be a function of the host nation and the breadth of security capabilities it can bring to bear. A full comparison of the vulnerability of a sea-based alternative to sabotage or terrorist attack will be an important consideration and will require security assessment for each host nation using ISO standards 28000 and 31000 which cover supply chain security and risk assessment. Risk mitigation requirements will also require individual analysis and deployment of fSMRs internationally. Importantly, it will also mandate updates to both the UN International Code for the Security of Ships and Port Facilities and the IMO International Ship and Port Facility Security Code (ISPS). Finally, regulatory inspections may also be more challenging. Some floating designs have limited plant access and would challenge inspection protocols. Other factors, such as the risk of an insider threat, would remain regardless of deployment option.

6. Conclusions and Policy Implications

Despite having the substantial benefits of a nuclear fuel cycle that is managed by existing nuclear-capable states, increased scope for cost control, and more limited risk of exposure in the event of an accidental release of core inventory, floating nuclear power plants would cost 1.5 to 2 times as much as equivalent, land-based sites if the former are built to stringent, quasi-U.S. military specifications for steel, welds, and quality assurance assuming no significant cost overruns are incurred for the land-based plants. Nuclear technology vendors pursuing this option commercially must recognize that, through a combination of prudent risk avoidance and regulatory caution, they would likely have to contend with satisfying both nuclear and quasi-military design specifications, incurring a substantial cost premium over alternate generation options. While some customers might be willing to pay this premium, the prospects of deploying these plants at a rate sufficient to meet the developing world's energy demand growth or mitigate climate change are probably not good. That said, our model does not quantify perhaps the most important benefit of the fSMR option, which is dramatically reducing the number of sites where special nuclear materials are stored, enhancing material control and accounting procedures, stretching the resources of organizations charged with oversight, and eliminating the risk of some material being compromised by political instability.

From our results, it is obvious that any vendor that chooses to offer fSMRs must invest substantial effort in defining standards for the commercial operation of this type of plant. Despite the potential safety and security benefits, there are uncalculated risks that the vendor will be required to address to perhaps multiple regulators' satisfaction. The costs and benefits that are used in arguing against or for the concept are generally small in absolute terms. Ultimately, what will make this concept successful are its control of overnight cost, which could prove difficult, and its potential to radically alter nuclear power's deployment paradigm, by removing custody of special nuclear materials from nations where institutional capacity is not yet developed enough to protect them and proliferation risks are an issue.

Construction of one floating nuclear platform is ongoing,(105) and there is now real interest in the concept.(106) The floating platform under construction is the Russian power barge - the *Akademik Lomonosov*. The barge is designed for use in remote areas that require electricity and process heat. It carries two small modular reactor plants - using a variant of a Russian ice-breaker nuclear plant (KLT-40S) - each with a power output of ~35 MWe. While development to date has been confined to existing nuclear-capable states, some developing coastal non-nuclear nations who have expressed interest in nuclear power (Vietnam, Saudi Arabia, Indonesia) may see an fSMR as a viable option to help address base load power production needs while maintaining a low carbon footprint. To ensure the development of standards supporting this eventuality, near-term international regulatory assessment is needed to: **(1)** establish standards for fSMR development and deployment. The International Atomic Energy Agency, International Maritime Organization and the United Nations should establish guidelines for platform construction, evaluate accident liability regimes and establish transportation, security and proliferation protocols for vendor and host nations. These organizations have previously established guidelines for marine shipment of nuclear materials, which can be used to establish a baseline for construction safety.(107) **(2)** Incorporate a floating siting option into ongoing international regulatory assessments of SMR and advanced reactor design licensing processes.

If this technology is developed, we think it most unlikely that the effort will be based in the U.S., both because of high costs, and because of the likely difficulties entailed in returning spent fuel. However, the U.S. is no longer the most active state in the commercial development of nuclear power. Other states might see the development of an fSMR industry sufficiently attractive in geopolitical terms to accept the return of spent fuel, and perhaps even back a commercial undertaking with government funds.

Chapter 5 References

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Chapter 5 Appendix A

Table A1. Plant siting criteria identified by the International Atomic Energy Agency

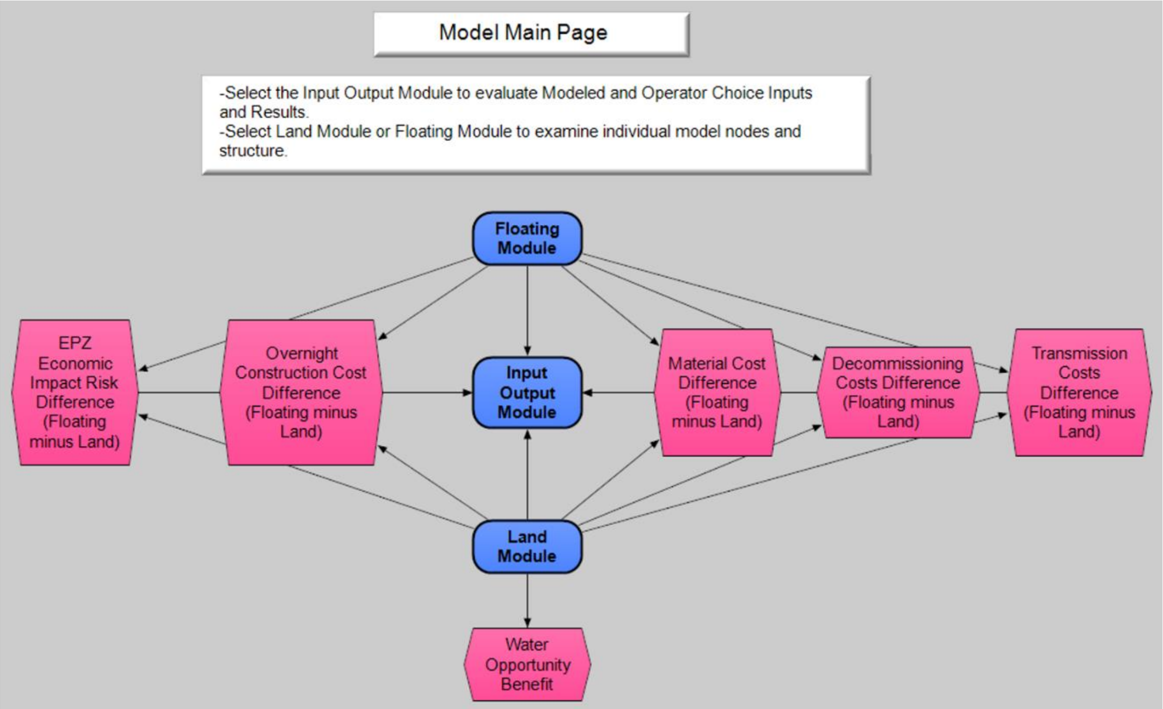
IAEA Nuclear Plant Siting Criteria(A1)
Nuclear Power Plant Parameter Envelope
Health, Safety and Security Factors
Magnitude and Frequency of natural external events
Human Induced events
Radiological Impact
Security and Safeguard
Essential Supplies
Engineering and cost factors
Suitability of water for cooling
Suitability of existing electricity Infrastructure
Location of major load centers and selling price
Suitability of transport infrastructure
Technology considerations
Impact of existing facilities
Site development and construction costs
Multi-unit sites
Physical Security and Protection considerations
Stakeholder opinion
Regional regulatory and legal processes
Socio-economic factors
Future land use planning and sites ownership
Regional economy
Local Society
Landscape
Noise
Environmental Considerations
General eco-system characteristics
Aquatic ecology and marine impact
Terrestrial ecology
Freshwater Impact
Air Quality

A1. International Atomic Energy Agency (2012) Managing Siting Activities for Nuclear Power Plants No. NG-T-3.7. *International Atomic Energy Agency*, Vienna, Austria, pp. 20-35.

Chapter 5 Appendix B

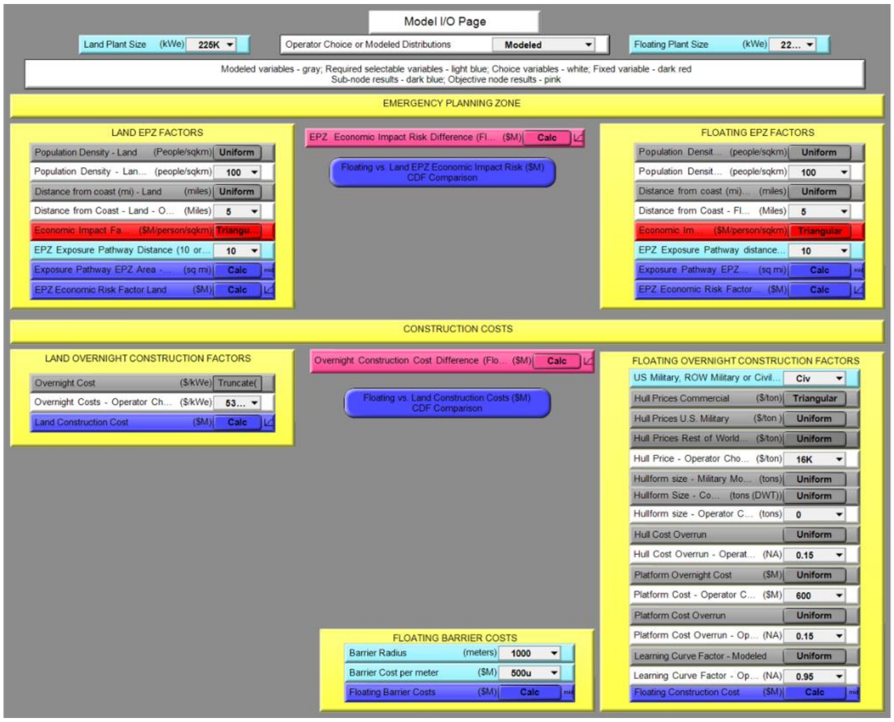
Analytica Model Structure

The main model page is shown in figure B1 below. Comparative factors include (from left to right) the Emergency Planning Zone, overnight costs (including transmission, decommissioning and material costs) and a separate assessment of water opportunity benefit for land site construction. On the model main page, selecting an individual node in pink and pressing the “show result” icon in Analytica yields a comparative assessment of the land and floating options with respect to that node. Double clicking the node for the input/output (I/O) module will bring you to the page shown in figure B2 below.



-Select the Input Output Module to evaluate Modeled and Operator Choice Inputs and Results.
-Select Land Module or Floating Module to examine individual model nodes and structure.

Figure B1. Analytica model main page: model is comprised of floating and land modules, as well as an input/out module and six decision nodes. Model allows for analysis using either operator choice or modeled distributions.



Model I/O Page

Land Plant Size (kWe) 225K
Operator Choice or Modeled Distributions: Modeled
Floating Plant Size (kWe) 22...

Modeled variables - gray; Required selectable variables - light blue; Choice variables - white; Fixed variable - dark red
Sub-node results - dark blue; Objective node results - pink

EMERGENCY PLANNING ZONE

LAND EPZ FACTORS
Population Density - Land (People/sqkm) Uniform
Population Density - Lan... (people/sqkm) 100
Distance from coast (mi) - Land (miles) Uniform
Distance from Coast - Land - O... (Miles) 5
Economic Impact Fa... ($M/person/sqkm) Triangu...
EPZ Exposure Pathway Distance (10 or... 10
Exposure Pathway EPZ Area - ... (sq mi) Calc
EPZ Economic Risk Factor Land ($M) Calc

EPZ Economic Impact Risk Difference (Fl... ($M) Calc
Floating vs. Land EPZ Economic Impact Risk ($M) CDF Comparison

FLOATING EPZ FACTORS
Population Densit... (people/sqkm) Uniform
Population Densit... (people/sqkm) 100
Distance from coast (mi)... (miles) Uniform
Distance from Coast - Fl... (Miles) 5
Economic Im... ($M/person/sqkm) Triangular
EPZ Exposure Pathway distance... 10
Exposure Pathway EPZ... (sq mi) Calc
EPZ Economic Risk Factor... ($M) Calc

CONSTRUCTION COSTS

LAND OVERNIGHT CONSTRUCTION FACTORS
Overnight Cost ($/kWe) Truncate(
Overnight Costs - Operator Ch... ($/kWe) 53...
Land Construction Cost ($M) Calc

Overnight Construction Cost Difference (Flo... ($M) Calc
Floating vs. Land Construction Costs ($M) CDF Comparison

FLOATING BARRIER COSTS
Barrier Radius (meters) 1000
Barrier Cost per meter ($M) 500u
Floating Barrier Costs ($M) Calc

FLOATING OVERNIGHT CONSTRUCTION FACTORS
US Military, ROW Military or Civil... Civ
Hull Prices Commercial ($/ton) Triangular
Hull Prices U.S. Military ($/ton) Uniform
Hull Prices Rest of World... ($/ton) Uniform
Hull Price - Operator Cho... ($/ton) 16K
Hullform size - Military Mo... (tons) Uniform
Hullform Size - Co... (tons (DWT)) Uniform
Hullform size - Operator C... (tons) 0
Hull Cost Overrun Uniform
Hull Cost Overrun - Operat... (NA) 0.15
Platform Overnight Cost ($M) Uniform
Platform Cost - Operator C... ($M) 600
Platform Cost Overrun Uniform
Platform Cost Overrun - Op... (NA) 0.15
Learning Curve Factor - Modeled Uniform
Learning Curve Factor - Op... (NA) 0.95
Floating Construction Cost ($M) Calc

Figure B2. Analytica model input/output page: model allows for analysis using either operator choice or modeled distributions. In the former mode, analysts can change individual numbers or distributions to reflect their assumptions or investigate the uncertainty around particular model elements.

As shown above, the I/O page allows assessment of values using either modeled distributions or operator choice for various cost factors, allowing review of outputs without going to individual sub-modules. Choosing between these two options is possible by toggling the relevant switch at the top of the I/O page, on which land site factors are situated to the left of the page, and floating site factors situated to the right. In the center column, in pink, are buttons that can be clicked to assess the differential costs of each modeled sub-module (EPZ, overnight cost, etc.), as well as blue buttons that generate cumulative distribution functions for the key variables in each sub-module. Another useful Analytica feature for the analyst is that any two variables can be compared. This is done by selecting both (using the Shift key) and then clicking the “show result” icon.

1) fSMR site: figure B3 displays all the sub-modules under consideration for the notional fSMR site. Note that, for the floating site, the only factor that is specifically a function of plant size is decommissioning cost.

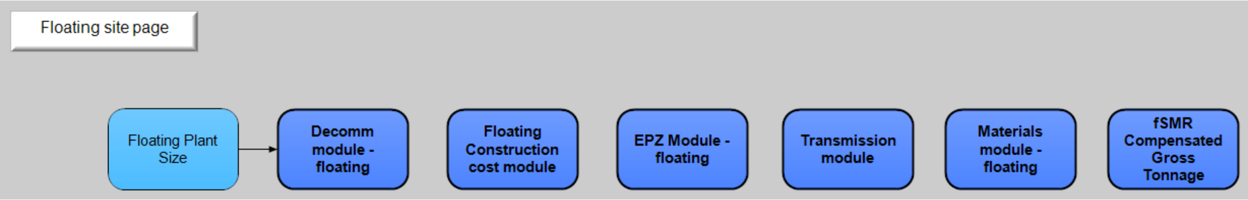


Figure B3. Analytica model fSMR page: this floating site module contains six sub-modules, as shown above.

Below, we list and discuss the six individual sub-modules within the fSMR module.

1.1) fSMR construction cost sub-module: the full breakdown of the construction cost sub-module can be seen in figure B4. When it comes to construction, two primary cost factors are included – one for the hull form (which is notionally modeled as an articulated, ballastable barge) and one for the staging and distribution (S&D) platform. Because there are multiple design alternatives when it comes to the development of the hull form and S&D platform, the ranges of costs are modeled as uniform distributions (again, there is an option to choose a specific parameter for each variable on the I/O page).

Modeled prices for the hull form can be adjusted to reflect civilian construction costs, U.S. military construction costs, or overseas (rest of world) military construction costs. This is done by selecting “Civ”, “Mil”, or “Rest of World” at the top of the sub-module page, respectively. If none of these values is desired, selecting the “Operator Choice” feature allows the user to define his own cost assumptions throughout. Note that the size of the military vessel is assumed to be in the range of 10,000-20,000 tons (light displacement), based on scaling estimates that place the barge’s size between that of a nuclear cruiser and that of a large amphibious vessel. A larger mass is assumed, since the vessel must be ballastable. Cost factors for commercial vessels are traditionally reported in deadweight tonnage (DWT). Therefore, a larger DWT value of 50,000-70,000 tons is assumed for our commercial vessel, which reflects the carrying capacity of the platform, which must contain both a large power plant and a significant volume of ballast water.

We program cost overrun factors in this sub-module that apply to each of the major cost inputs, as well as a learning curve factor that would apply uniformly across the entire sub-module. These may be altered or removed by switching from default values to

Operator Choice. Finally, to reflect the unique security issues associated with a floating platform, an additional floating security barrier cost was incorporated. The circumference of the barrier (and therefore its cost) can be modified. Our estimate of barrier cost came from conversations with a primary barrier contractor for the United States Navy.

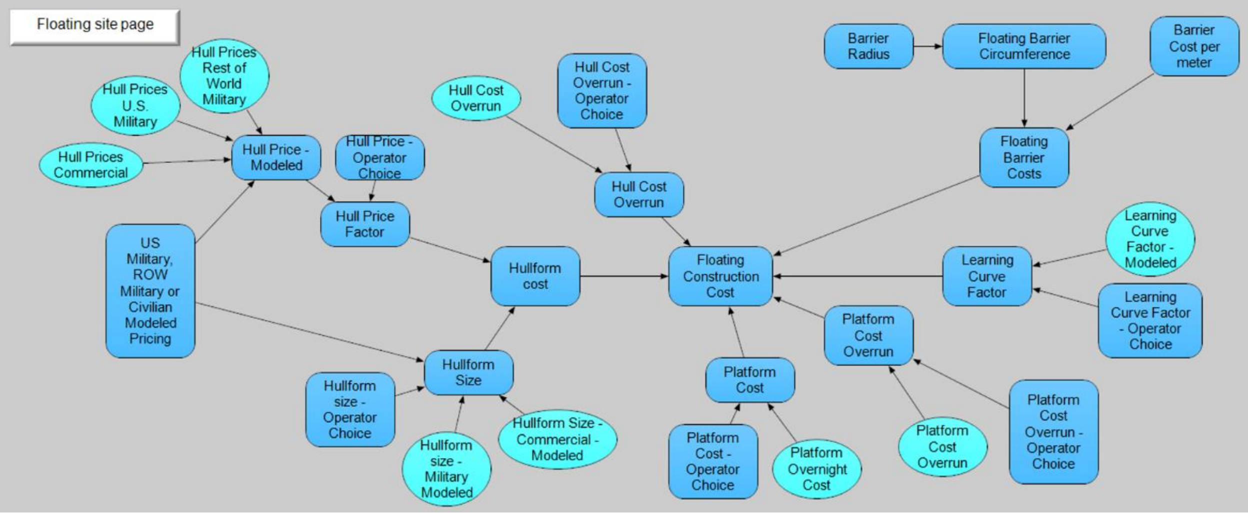


Figure B4. An influence diagram of the fSMR construction cost sub-module. Note possibility of using either default or "Operator Choice" inputs.

1.2) fSMR transmission cost sub-module: Our analysis of the next factor in the fSMR module, electricity transmission costs, is shown in figure B5 below. This sub-module estimates the range of costs for new cabling infrastructure, based on the distance of the fSMR from the first major shore substation.

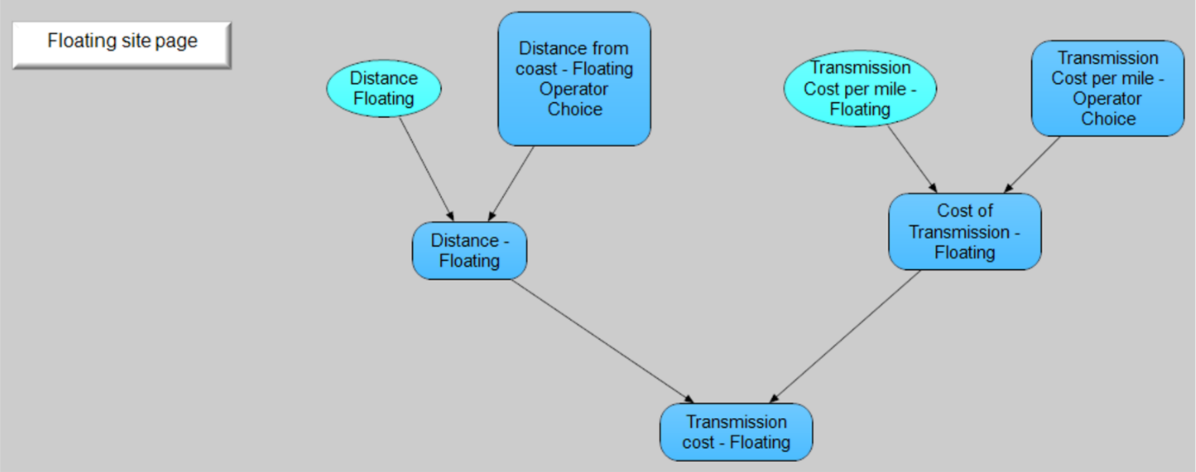


Figure B5. An influence diagram of the fSMR transmission cost sub-module.

In figure B5, note the possibility of using either the default modeled values or "Operator Choice" inputs for the cabling distance and its assumed costs. Our research suggests that costs vary widely depending on geography, distance, and type of cable (above ground, buried, submarine). Hence, a wide range of costs was used for the modeled values.

1.3) fSMR decommissioning cost sub-module: decommissioning costs in this model are estimated using U.S. 10 CFR 50.75 and NUREG-1307 guidelines for decommissioning cost funding. While these estimates might not be appropriate for non-U.S. plants, it nonetheless provides a reasonable starting point for comparing land-based and fSMR deployments.

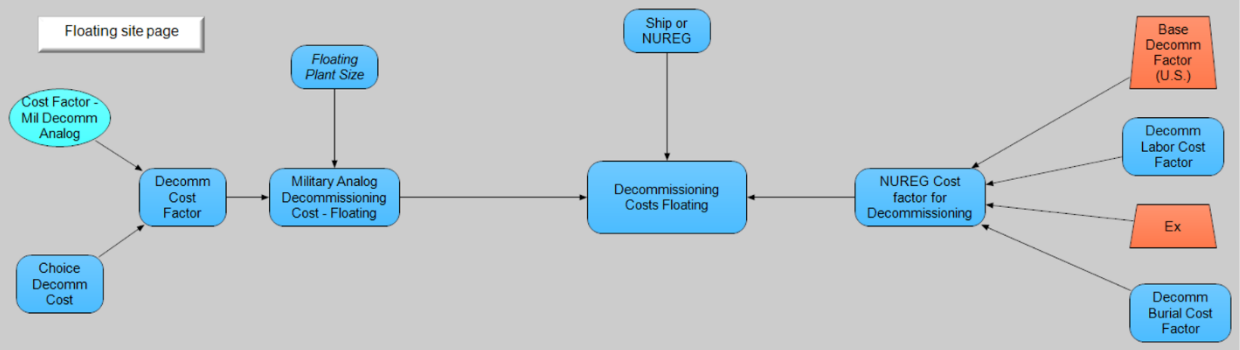


Figure B6: An influence diagram of the fSMR decommissioning cost sub-module. Analyst can use either existing regulatory standards for commercial plants or military inactivation costs as analogs.

Our model uses NUREG cost calculations, and allows the analyst to select the labor factor and decommissioning burial costs in determining funding requirements. These factors change regularly, and updates are available at the Bureau of Labor Statistics, not to mention updated versions of NUREG-1307. The model factor for energy adjustment is a nationwide value, but the labor and waste burial factors change regionally, and are therefore modeled as selectable items in the model. In line with the Code of Federal Regulations, the base decommissioning factor equation is given by:

$$\boxed{(75 + 0.0088*1{,}200)\ (\text{million dollars})}$$

where *1,200* reflects the minimum power allowed for calculation of funding levels (i.e. 1200 MWe). This equation is based on 1986 funding levels, and is corrected using the Burial, Energy and Labor cost adjustment factors. The model is designed to allow selection of a range of labor and burial cost factors. Note that the largest variation is in burial cost factors which range from a value of ~7 to 30, depending on region, while the labor factors vary across a much smaller range (from ~1.9 – 2.6). These factors are combined with the baseline equation as follows:

$$Base\_Decomm\_Factor * (0.65*Labor\_Factor + 0.13*Energy\_Factor + 0.22*Burial\_Factor)$$

Should a comparison be desired with typical costs for inactivation of a floating nuclear platform, using U.S. nuclear platforms as analogs, this can also be supported by the model (see the left panel in figure B6). The values used in this case reflect standard cost factors for ship inactivations drawn from U.S. Navy budget documents, coupled with a scaling factor for the size of the plants in question. This assumes fSMR decommissioning would mirror a nuclear military ship inactivation model.

1.4) fSMR material cost sub-module: while material costs are assumed to be included in the estimate of the overnight construction costs, a separate assessment was conducted to compare material costs for the two deployment options. The fSMR material cost sub-module is shown in figure B7.

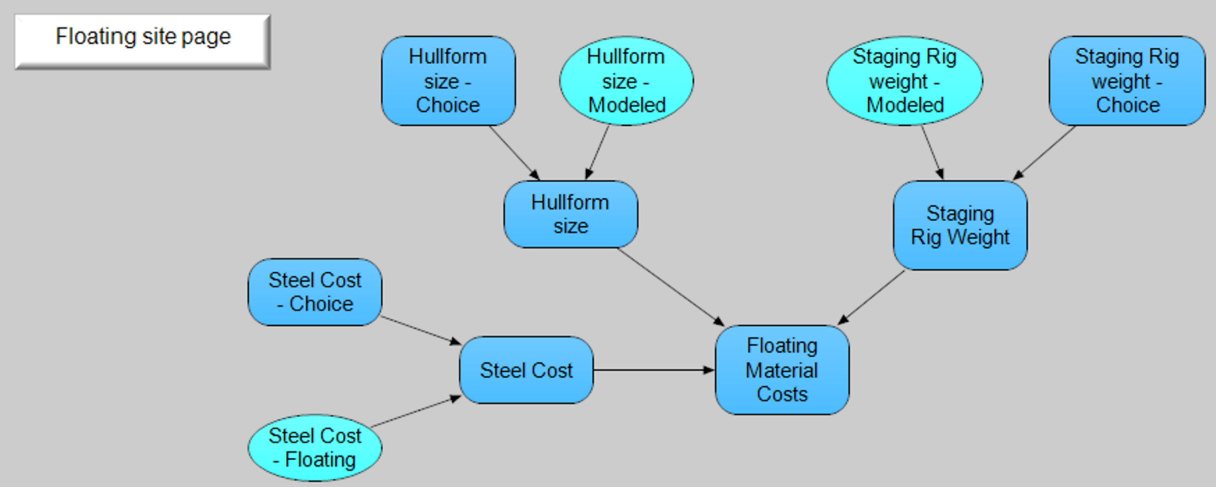


Figure B7: The fSMR material cost sub-module.

The predominant material for the floating site is assumed to be steel. A range of floating hull form sizes is modeled (10-20K tons), as well as a range of S&D platform sizes (20-30K tons). These are then coupled with a chance node distribution for steel cost that varies from $250-800 per ton. This wide range, taken from multiple world steel cost sources, is intended to cover the broad range of prices for steel variants that are used in construction, from plate to beam to rebar. As with other modules, there is also the option to input a deterministic value through the “Operator Choice” option on the I/O page.

1.5) fSMR Emergency Planning Zone sub-module: this module monetizes part of the EPZ risk implications using U.S. NRC standards for EPZ planning, considering both the 10-mile radius Plume Exposure Pathway and the 50-mile radius Ingestion Exposure Pathway. Analysts can choose which EPZ distance to consider on the I/O Page. Sub-module nodes are shown in figure B8.

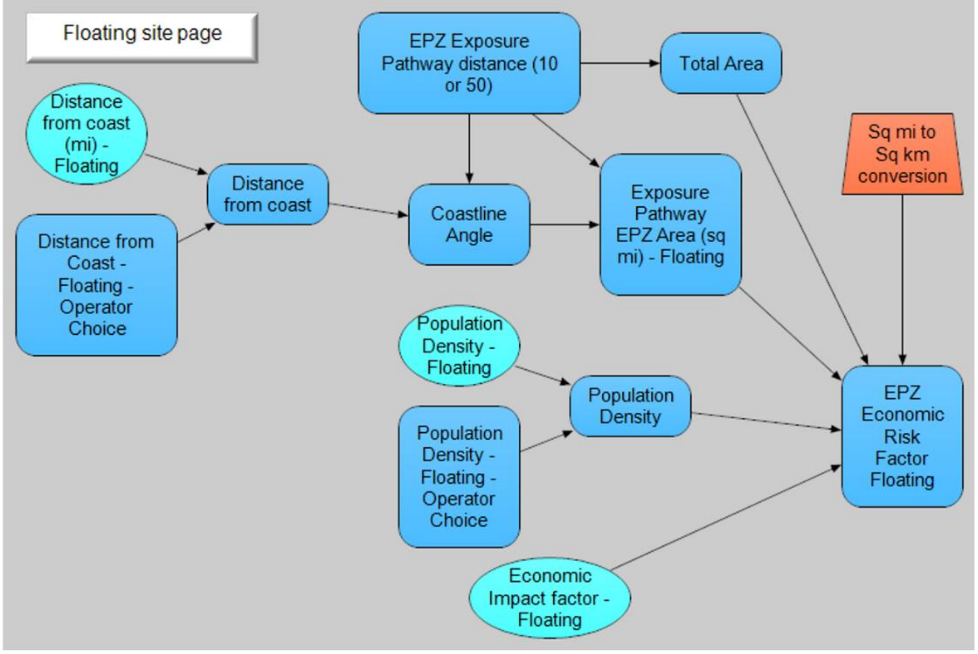


Figure B8: The fSMR EPZ sub-module. The module considers an fSMR site's distance from the coast, population density, and economic impact when partially monetizing EPZ risk implications.

To monetize EPZ risk implications, a planning area is determined based on the 10 and 50-mile EPZ radius, and the distance from shore (this assumes that the sites under consideration are coastal). Using the geometry reflected in the diagram below and the equation that follows, areas of the EPZ zone that are unpopulated are removed from consideration. For the land-based site, as distance inland increases, the area of this circle that needs to be considered increases. For the fSMR, as distance offshore increases, this area decreases.

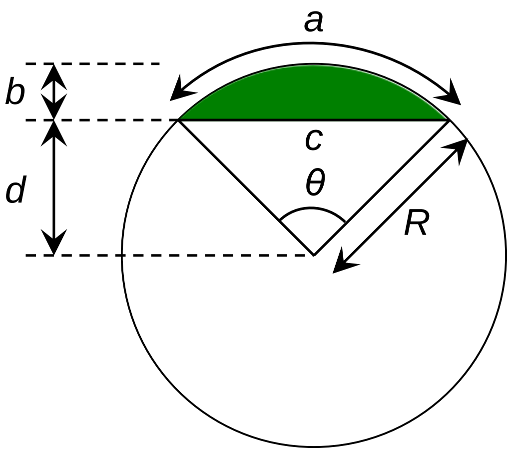


Figure B9: Assessing the area affected by a potential accidental release of radioactive material. The farther from shore the fSMR is, the smaller the population in the area covered by the fSMR's Emergency Planning Zone.

Equation for Area Calculation - fSMR:

$$[((EPZ\_Exposure\_Pathway^{\wedge}2)/2) * Coastline\_Angle*Pi/180] - (EPZ\_Exposure\_Pathway^{\wedge}2)/2 * \sin(Coastline\_Angle)$$

Note that, in figure B9, the value of R will vary based on the EPZ range chosen (10 or 50). Once the coverage area is calculated, it is used in combination with both the population density for the area under consideration and the economic impact factors (measured in $/people/sqkm), which are derived from Three Mile Island, Fukushima, and Chernobyl remediation, compensation, and economic impact estimates. While this calculation might overstate potential costs, since not all areas under consideration will be impacted (based on prevailing winds, accident magnitude, plant size, etc.), it does provide a notional comparative value for use in assessing the risk of each siting option. The equation for EPZ cost risk factor (in $M) can be written as follows:

$$(Economic\_Impact\_Factor*Population\_Density) * (Exposure\_Pathway\_EPZ/Total\_Area) * mi^2\_to\_km^2\_conv$$

1.6) fSMR Compensated Gross Tonnage cost calculation sub-module

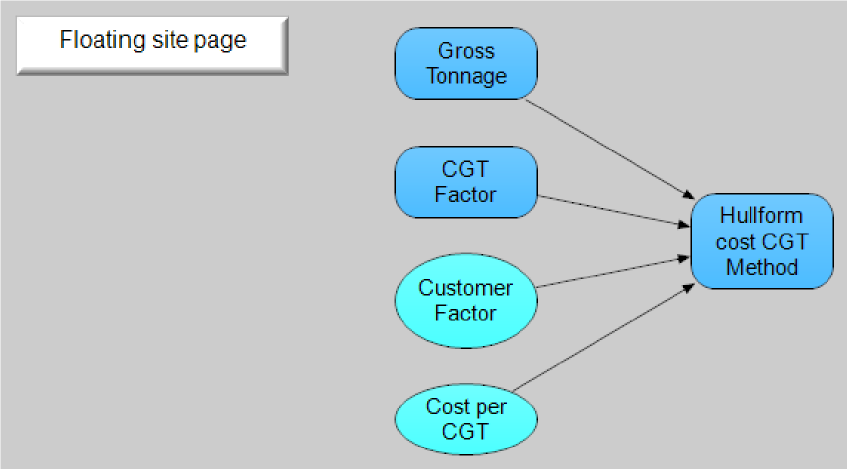


Figure B10: The fSMR Compensated Gross Tonnage cost calculation sub-module. The module considers an fSMR's cost using the OECD Compensated Gross tonnage methodology as an alternative to the cost module shown in figure B4.

This module conducts an alternative calculation of fSMR barge cost based on OECD Compensated Gross Tonnage considering additional customer factor ranging from 1.08 to 1.18 to reflect greater design standards and scrutiny, cost variation based on international norms that range from $125-450/CGT using China, South Korea, and Japan indices. Tonnage value is dimensionless value based on estimated volume of the barge platform (nominally 20,000). CGT factor is selectable from 0.3 to 50. This module is used to determine what CGT factors would be applicable for a fSMR barge that would be competitive with land site costs. The calculation is given by:

*CGT_Factor*Cost_per_CGT*Customer_Factor*Gross_Tonnage*

2) Land SMR site: figure B11 displays the land site module's components. It mirrors the fSMR module with one exception, which is the inclusion of a water opportunity benefit sub-module, described below.

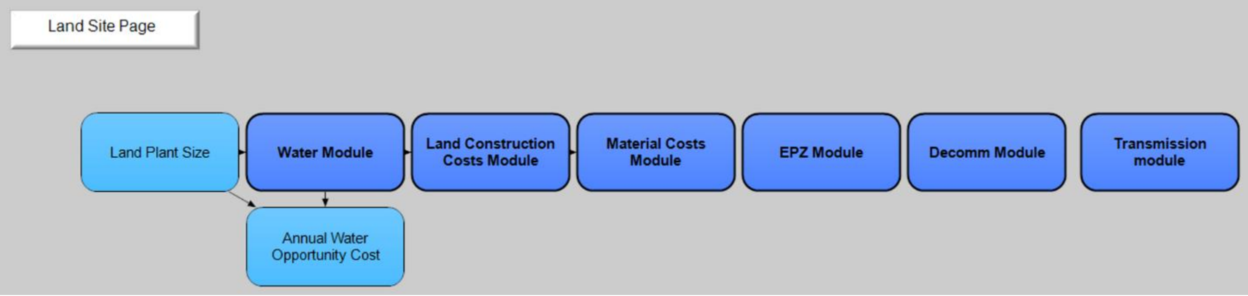


Figure B11: Analytica model land SMR site page: this land site module contains the same five sub-modules as the fSMR site, and an additional "water opportunity benefit" module to assess the implications of using freshwater for cooling.

2.1) Land site construction cost sub-module: as shown in Figure B12, the major factor in the land site construction cost sub-module is the assumed overnight cost. There is a wide range of estimates for land-based SMR overnight costs. We modeled the overnight costs using values from Abdulla and Morgan's 2013 expert elicitation. In this elicitation, experts accounted for the potential cost overruns when it comes to overnight cost; therefore, no additional overrun module was incorporated in our model. Should a user wish to specify additional cost overruns, this can be done by selecting "Operator Choice" and inputting a (higher) overnight cost estimate. The overnight costs are also adjusted to account for the percentage of overnight costs typically attributed to site construction, management and development, nominally 64% (based on a Black and Veatch assessment conducted for NREL). This has the effect of removing SMR plant components from the cost assessment, as was done for the fSMR sub-module, which essentially only looked at vessel costs.

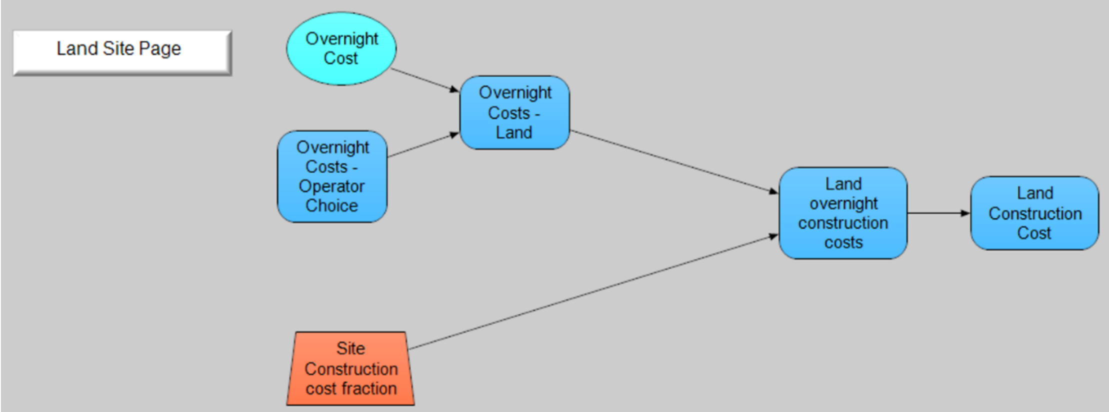


Figure B12: An influence diagram of the land site SMR's construction cost sub-module.

2.2) Land site transmission cost sub-module: the transmission module for the land site option is essentially identical to that used for the fSMR calculation (compare figures B5 and B13). The transmission cost is likely to be much lower for the land site, due to the lower average costs of land-based cabling (even assuming it has to be buried in urban settings). Values can be adjusted in the I/O page.

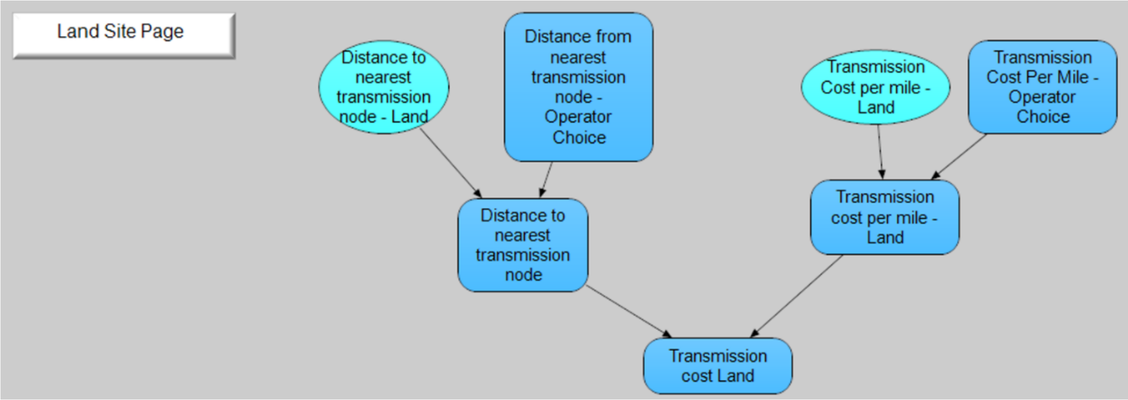


Figure B13: An influence diagram of the land site SMR's transmission sub-module.

2.3) Land site decommissioning cost sub-module: this sub-module is shown in figure B14 below. NUREG-1307's assessment factors are considered for the land case. Please consult the discussion in the fSMR decommissioning section (section 1.3) for an explanation of how decommissioning costs are calculated.

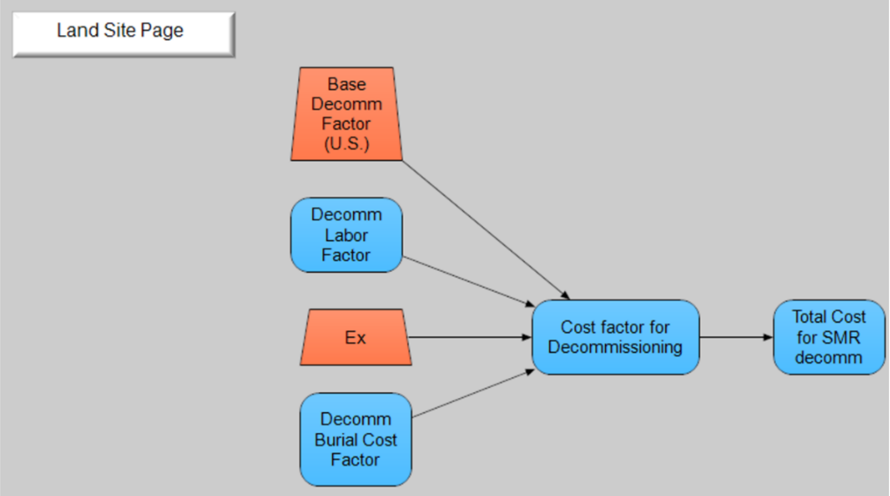


Figure B14: An influence diagram of the land site SMR's decommissioning sub-module.

2.4) Land site material cost sub-module: the factors used for assessing the concrete volume and steel mass are taken from studies conducted by UC Berkeley and Oak Ridge National Laboratory, which outline the amount of these materials that are required for nuclear power plant construction. While these same studies also have factors for the reactor plant, turbine, and electric plant materials, an initial assumption was made that these would be comparable between the two site options and that the predominant difference would be in the "structures and site" materials portion. The scaling factor for site materials was taken from Peterson's recommendation in a separate study of the Advanced High-Temperature Gas Reactor. The calculations used to determine quantities are as follows:

*Steel: 17,362 * ((Plant_Size/1,000,000)^0.82)*

*Concrete: 61,030 * ((Plant_Size/1,000,000)^0.82)*

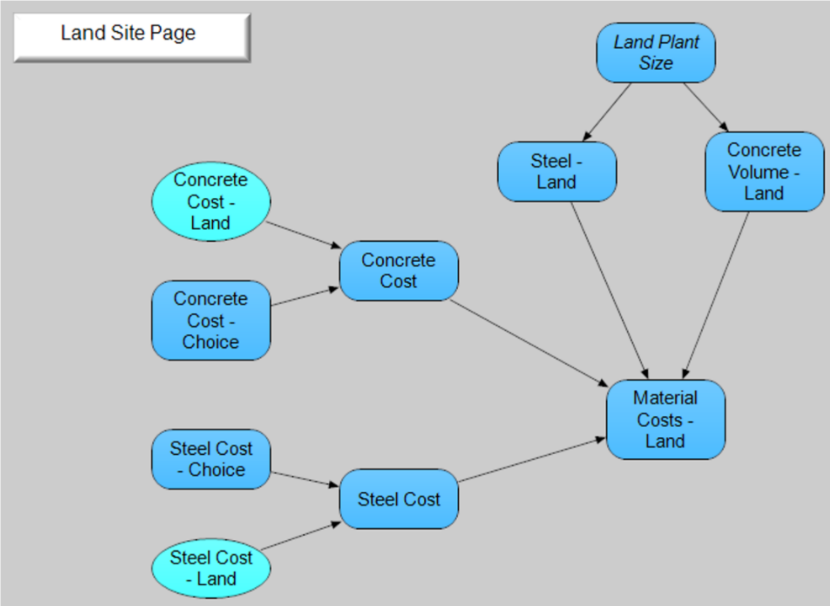


Figure B15: An influence diagram of the land site SMR's materials sub-module, which evaluates the amounts and costs of the concrete and steel required to construct this plant.

Cost factors were modeled in a similar fashion to the fSMR site. Note that concrete pricing assumes only concrete and not reinforcing steel, which is incorporated in the steel node. As with the other sub-modules, "Operator Choice" is allowed for all variables.

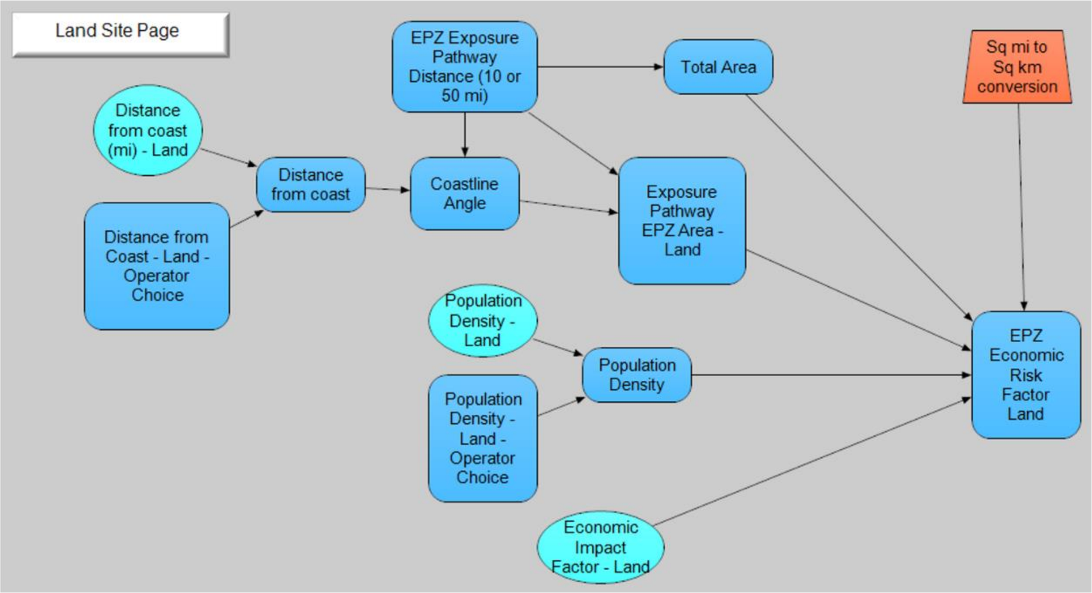


Figure B16: The land site SMR's EPZ sub-module. The module considers the SMR site's distance form the coast, population density, and economic impact when partially monetizing EPZ risk implications.

2.5) Land site Emergency Planning Zone sub-module: this module, shown in figure B16 above, is comparable to the corresponding fSMR sub-module described in section 1.5 above. The only significant difference is in the calculation of the area, which for the land site works in the opposite fashion to the fSMR site since greater distances from the coast imply greater exposure not only to the urban population but also to rural areas and agricultural land. The equation is as follows:

$$(EPZ\_Exposure\_Pathway^{\wedge}2)*Pi - (EPZ\_Exposure\_Pathwa1^{\wedge}2)/2*[((Coastline\_Angle1*Pi)/180) - Sin(Coastline\_Angle1)]$$

Like the fSMR site, cost values are based on the TMI, Fukushima, and Chernobyl incidents. Cost is calculated in a similar fashion to the fSMR EPZ Sub-module (section 1.5). No assessment of wind or weather parameters is included, which could drastically impact actual exposure calculations. This sub-module is intended to demonstrate the impact of moving a site away from population centers.

2.6) Land site water opportunity benefit sub-module: because water withdrawal is a significant issue for plant siting, this module is designed to assess the scope of water withdrawal and the opportunity cost of using this water for power production, as opposed to other urban needs. Water withdrawal factors are considered only for the land-based site. The sub-module is shown in figure B17.

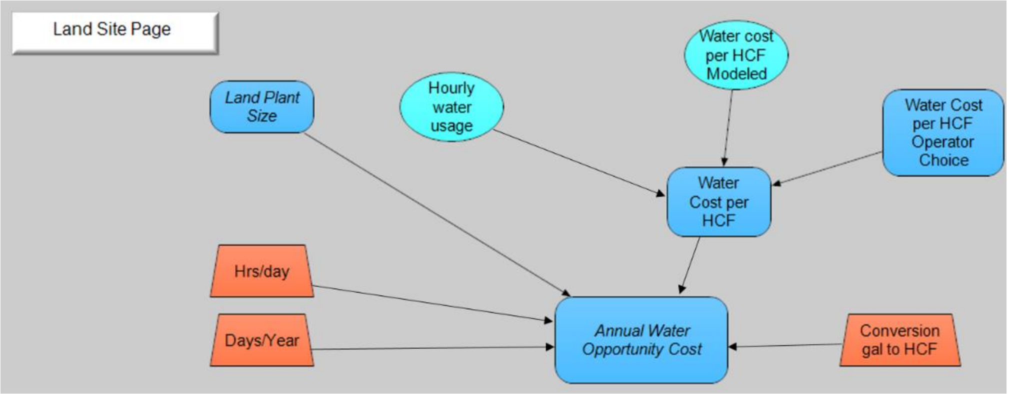


Figure B17: The land site SMR's water opportunity benefit sub-module.

Using a range of reference water withdrawal factors and assumed consumption factors (1% of the water used in a plant is nominally "consumed"), our model approximates the volume of water consumed by a land-based site (assuming this is fresh water), and monetizes this to determine the value of the water consumed during power production, which might have been used for other purposes. This is an important consideration in arid climates with limited fresh water availability. Water usage is approximated using a triangular distribution, which adopts as its boundary values estimates from NREL technical reports. Costs are approximated using values for commercial water withdrawal rates in California and Washington states in the U.S. The modeled range is broad and reflects the cost of water in many other countries as well (such as Denmark and Germany). Calculation of the annual water opportunity benefit is as follows:

*[((Plant_Size/1000)*Hourly_water_usage*Hrs_day*Days_Year)/Conversion_gal_to_HCF] * Water_cost_per_HCF/*

3) Marine Accident Module: This module, depicted in Figure B18, calculates the expected time following an accident related release of radionuclides from an fSMR until sampling of fish in the affected area is likely to reach contamination levels that are below established thresholds. Values calculated are specific to Fukushima in that they model release and decay of concentrations using Fukushima data which is correlated specifically to the marine conditions at that site.

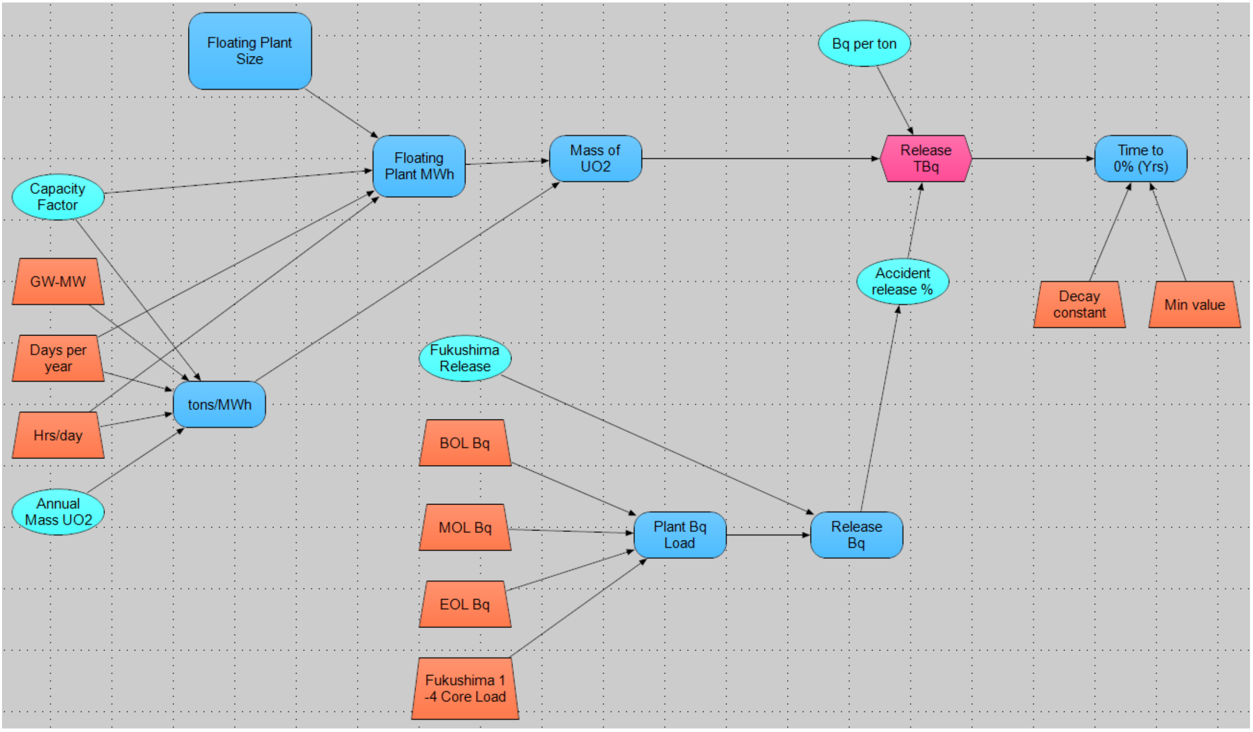


Figure B18. fSMR marine accident release.

The module first uses values for a typical GW scale power plant to develop a “tons/MWh” calculation that is based on a modeled depletion of 20-30 tons/year of UO2 in a 1000 GW plant and also a modeled capacity factor that ranges from 0.86-0.92. Assuming comparable core loading for an SMR, and scaling this to the smaller size of the SMR modeled here (225 MWe), a presumed core loading (using a 2-year service life) is calculated (node: Mass of UO2). Next, an estimate of the core loading of Fukushima plants 1 through 4 is completed, using average values of Bq content for a Beginning of Life, Mid-Life and End of Life reactor. This is then used coupled with a distribution of Fukushima release (range 80-130 PBq) presuming the entire release was from these four cores (ignoring any fuel pool release) to determine a uniform release possibility of 10-100% of the level of Fukushima. This provides a very conservative (high) estimate of the size of release. This maximum value is used as the high end of a modeled distribution. Using a uniform distribution for Bq content for the fSMR core (assuming an accident could happen at any time in core life), a final calculation is completed to determine a release (in TBq). Using a decay factor calculated from actual sample data from Fukushima fisheries sampling, we estimate the time that an fSMR would take to decay to less than the Japan Atomic Energy Agency and Fisheries Agency determined limits for Bq content (<100 Bq/kg).

CHAPTER 6

Conclusions and Policy Implications

1. Research Findings. The overall context of our analysis has been to examine nuclear energy as a potential source of low carbon electricity generation that may aid in meeting climate change mitigation goals. However, if nuclear power is to play any significant role in decarbonization, it must overcome a number of long-standing challenges. Based on the summary findings detailed below, we conclude that the development and implementation of a comprehensive set of technical and policy solutions will be needed to ensure that by mid-century, new technologies and new deployment methods are mature and available to support expanded nuclear development.[10]

1.1. Finding 1 – DOE NE Budget Assessment. Our analysis of DOE NE, the lead government office for development of advanced nuclear technology, indicates that the office lacks the funding levels and long term commitment necessary to develop and deploy advanced, non-light water reactor designs in a timely manner. It has dedicated only $2 billion over the past 18 years to ***all*** advanced reactor and fuel initiatives, which by its own estimates is not enough to ready even ***one*** such design for commercial deployment. Large sums are expended to maintain research infrastructure that only marginally supports advanced reactors. Many designs are being pursued at a low level of funding, and the fuels program, while successful, is developing products that might never be commercially deployed.

Recommendations and Policy Implications. Echoing the recently released report by the Secretary of Energy Advisory Board (SEAB), our analysis suggests that the problem facing NE is sufficiently acute to warrant a new approach. Because dramatic increases in its funding level are unlikely, and because the SEAB's suggestion that the creation of a quasi-independent, separately funded advanced reactor effort is equally unlikely, NE should exercise stricter programmatic discipline, by which we mean channeling its resources to fewer, carefully chosen, efforts in the hopes of generating greater impact. To that end, it is essential that NE establishes a transparent process for evaluating the various advanced reactor concepts it supports across key performance

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[10] Major findings are detailed here. Individual chapter summaries contain all findings.

requirements. The goal of this process should be to provide a robust channel for debating the economic, safety, security and waste implications of various designs. An independent panel of experts—perhaps a presidential blue ribbon commission or a committee of the U.S. National Academies—should then identify, in consultation with key stakeholders, the one or two technologies that best meet these key performance requirements. This would unburden NE of the need to down-select technologies itself. Such an arms-length approach tracks a middle path between the status quo and SEAB's radical but politically difficult recommendation. If adopted, it would allow NE to better focus its limited funding and would be in harmony with the industry's desire for risk-informed, performance-based guidance from government.

1.2. Finding 2 – Expert Interviews on the State of Advanced Reactor R&D.

Results from interviews with experts in the advanced nuclear enterprise echoed the findings from our quantitative analysis. Experts indicate that the future in quite uncertain for nuclear energy in general and for advanced nuclear in particular. The primary government entity responsible for advanced nuclear development, DOE NE, is seen as having been ineffective in leading the effort to field new designs because of the absence of strong Executive and Congressional branch support and direction. The office is also poorly focused in managing the AR programs that they do fund, and appear to have far greater comfort in managing the iterative development of light water designs. Even with significant emphasis on the development of advanced designs, experts indicate that there is a low probability that advanced reactors will play a near term role in a low-carbon energy system.

Recommendations and Policy Implications. In addressing the need for change in the manner that NE executes its mission, experts saw a need to clarify NE's overarching mission for the coming decades: support for the development and construction of advanced fission prototypes. Once that understanding permeates NE, experts elaborated two additional needed actions.

First, consolidate existing infrastructure. The extensive, aging facilities that currently exist are of limited utility for advanced nuclear development. Research in advanced fission is spread across multiple national labs and universities. While urgently needed, consolidation that would free up some additional funding to develop the demonstration and test facilities the experts is likely to be extremely challenging. Success is likely to require deft leadership and institutional innovation.

Second, given the limited technical expertise within NE and the wide range of stakeholders vying for its appropriations, rigorous peer-review standards must be adopted to ensure that each of NE's projects contributes to meeting its goal of supporting the development of advanced fission prototypes. Experts laid out three possible leadership alternatives for executing NE's mission with new standards, including a status quo approach, one with NE as a facilitator, and perhaps one with outside agency support such as the National Science Foundation in developing these standards and assessing progress. A number of experts recommended a significant change in the structure and mission of NE, advising that they move to a supporting role, enabling private sector innovation by making technical infrastructure and laboratory expertise more readily available. This option has the advantage of being driven by the newest and most active of advanced reactor developers, who are most active in trying to improve the prospects of nuclear energy in the U.S. Many of the more senior experts, felt a more radical change in structure was needed. While they recognized that NE might still play a role, they believe overall leadership and oversight should come from a new, independent organization. This structure would be similar to the one spelled out by a recent Secretary of Energy Advisory Board Report (SEAB), which envisions a quasi-public corporation that would lead the effort, beginning by re-focusing funding on a small number of advanced reactor initiatives.

Regardless of strategy, achieving these revised goals, either under a status quo leadership structure or one of the new approaches described by the experts, will require political support. Participants said that a new, coherent national energy policy is needed and it is apparent that a key component of this policy must address NE's leadership shortfalls in a way that will allay experts' concerns.

1.3. Finding 3 – SMR Development Readiness. Our assessment of nation/state readiness for expansion of nuclear energy using small modular reactors indicates that while many non-nuclear nations have the capacity to join the existing group of nuclear nations, the vast majority of need in fossil generation reduction, and largest portion of the market, still resides with the core group of large developed nations that continue to operate nuclear power plants today. Even if nuclear deployment were dramatically expanded, and 30% of existing fossil generation were replaced with nuclear power, the impact in terms of mitigating emissions from the power sector are large but would still leave 80-90% of world emissions to be addressed.

Recommendations and Policy Implications. Nuclear deployment strategies that focus on emerging nuclear energy states for deep decarbonization are well meaning, but the overwhelming share of decarbonization will have to be borne by nations that are already nuclear capable. In light of this, at least for the next few decades, a focus on maintaining the viability of nuclear power in existing large markets, like the US, the EU, China, and India, might accomplish more for both the technology and climate than seeking to export reactors to emerging nations. Should SMRs be found to be a viable business option, consideration should be given to long-term trend assessment for economic, environmental, and institutional readiness.

1.4. Finding 4 – The role of institutions in nuclear development readiness. Our SMR development readiness assessment indicates that while the path to nuclear development may not be closed if nations are challenged economically or have shortcomings in institutional readiness, development in these nations may carry greater financial and security risk.

Recommendations and Policy Implications. The factors we used in this assessment should be incorporated into the decision process for any vendor nation and for international bodies such as the IAEA who may be asked to support new nuclear development. Among those nations that are less stable in governance, there is also the potential for greater risk in proliferation – a key development consideration for the international community. Our initial guideline for variable selection was the IAEA standards for sustainable nuclear development. Given the impact that institutions may have on development and proliferation risk, these IAEA standards should be updated to reflect the incorporation of governance factors in factors used to assess readiness for sustainable nuclear development.

1.5. Finding 5 – The BOOR Model and potential of floating SMRs. Our assessment of deployment readiness indicates that there are a large number of nations that would benefit from a novel deployment model such as a floating Small Modular Reactor (fSMR). This deployment option, perhaps following a build-own-operate-return (BOOR) management option, would allow expanded use of nuclear in mitigating carbon emissions, reducing freshwater use, and eliminating seismic and tsunami risk. Detailed modeling of factors that affect fSMR development indicates that an fSMR built to predominantly commercial standards may also address the significant risk of cost and schedule overrun faced by large scale terrestrial nuclear construction. However, if these units are built to military nuclear standards, costs would be prohibitive.

Recommendations and Policy Implications. As nations consider costs and benefits of nuclear development, consideration should be given to a floating design. Before embarking on such a project, however, standards for construction and safety must be considered and incorporated into all licensing and regulatory regimes. Since there is ongoing global development of these platforms, international regulatory bodies, including the United Nations, IAEA, and International Maritime Organization should act to develop standards that will ensure that development and security risks are adequately identified and addressed.

2. Summary. Nuclear power can make a significant contribution to a low carbon energy future if key economic, security, and institutional issues are addressed. A viable global nuclear market exists and development leveraging small modular reactors may address some of the economic shortcomings that have plagued past large scale nuclear development. SMR deployments could include using unique options such as floating reactors. However, before deployment across a broader group of nations using terrestrial or floating designs, significant consideration should be given to institutional readiness which can have a major impact on long-term safety and viability, especially in managing the complexities of the global fuel cycle. In order to mitigate some of these concerns, existing vendor nations should consider novel options such as build-own-operate-return in dealing with new entries to the nuclear cohort.

While efforts are underway to develop advanced nuclear designs worldwide, advanced reactor research and development in the US is stagnant. It is unlikely that this type of design will be a part of any nuclear contribution in the US for at least several decades. Indeed, as other nations such as China and Russia forge ahead with nuclear power, the future of any form of nuclear development in the US is quite uncertain. Given the current trajectory, with limited political support, unfocused funding, stagnant leadership, and aging infrastructure that is of limited utility—a likely outcome is a slow demise of both nuclear power and nuclear R&D in the U.S., and the nation’s gradual shift from a position of leadership on nuclear matters to the periphery.