Evaluating changing paradigms across the nuclear industry

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Jessica R. Lovering

B.A., Astrophysics, University of California, Berkeley
M.S., Astrophysical and Planetary Sciences, University of Colorado, Boulder
M.S., Environmental Studies, University of Colorado, Boulder

Carnegie Mellon University
Pittsburgh, PA
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Abstract

The International Energy Agency (2015) states that global nuclear energy capacity will need to double by 2050 to achieve meaningful reductions in carbon emissions. To that end, there are over thirty countries around the world pursuing their first commercial nuclear power plants, and almost all will import their first reactors. The U.S. nuclear industry simply cannot compete with countries like Russia and China when it comes to exporting large light-water reactor (LWR) projects. Yet there is a boom of companies working on advanced nuclear technologies in the U.S., many aiming to be cost-competitive with fossil fuels. Some of these designs, particularly microreactors less than 10MW, could be demonstrated on much shorter timelines and at much lower costs than previously assumed, proving the technology domestically while also validating a potential export product. This thesis will investigate the nexus between these two emergent trends in the global nuclear industry: a shift away from the US as the dominant exporter and the implications for international security, and the move toward smaller, factory-produced commercial nuclear reactors.

In Chapter 2, I explore the role that nuclear exports have played historically in strengthening international nuclear material control regimes, and the implications of a decline in U.S. exports. I present results from a participatory expert workshop that evaluated policies that might be adopted to regain U.S. influence, including expanded U.S. exports of new nuclear technologies. However, the results from the workshop indicated that diplomatic strategies would be more feasible to implement over strategies that relied on a revitalized U.S. nuclear export market. The experts concluded that advanced reactor technologies would not be commercially viable on relevant timescale. Yet recent policy and commercial development suggest that microreactors could be commercialized on much shorter timelines.

To understand the potential of these microreactors, in Chapter 3, I perform a techno-economic evaluation of small-scale nuclear off-grid and community microgrid applications. I develop case studies for potential niche markets for the technology: two off-grid diesel-

powered Canadian communities, a large hospital in Alaska, and a college campus in Wisconsin. The results indicate that microreactors can be cheaper and more reliable compared to 100% renewables systems, and they can also be cost-competitive with diesel where fuel costs are greater than \$1/liter and the microreactor capital cost is less than \$15,000/kW. However, the levelized cost of electricity (LCOE) for microreactors is most sensitive to the initial capital cost, and whether this technology will ever move beyond niche markets will depend on the learning effects accrued through factory fabrication.

Thus, in Chapter 4 I will examine the hypothetical trade-offs between economies of scale and economies of volume for potential factory-fabricated microreactors. I calculate the break-even volumes necessary for microreactors to become cost-competitive with large reactors and with fossil fuels, using parameters from historic nuclear builds and analogous energy technologies. Drawing from the literature on learning rates across energy technologies, I predict potential learning rates for various sized microreactors based on historical relations. Finally, I will outline some of the policy challenges of this new nuclear paradigm, along with areas for future study regarding the near-term deployment of microreactors.

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List of Abbreviations

BWR Boiling Water Reactor

DOD Department of Defense

DOE Department of Energy

FOAK First-of-a-Kind

HOMER Hybrid Optimization of Multiple Energy Resources

HTGR High-Temperature Gas-Cooled Reactor

IAEA International Atomic Energy Agency

IEA International Energy Agency

IPCC Intergovernmental Panel on Climate Change

LCOE Levelized Cost of Electricity

LWR Light-Water Reactor

MWe Megawatts electric

MWth Megawatts thermal

NELA Nuclear Energy Leadership Act

NPT Nuclear Non-proliferation Treaty

NRC Nuclear Regulatory Commission

NRIC National Reactor Innovation Center

OECD Organisation for Economic Co-operation and Development

PPA Power Purchase Agreement

PWR Pressurized Water Reactor

SMR Small Modular Reactor

Chapter 1

Introduction

The Intergovernmental Panel on Climate Change (IPCC) argues that the global energy system needs to reach net-zero emissions by 2050 to avoid the worst impact of climate change (IPCC 2018). Given that global demand for electricity is expected to double by 2050, and almost 90% of that growth will come from outside of high-income countries (Kempfer et al. 2020), decarbonization poses a huge challenge. The power sector should have been the lowest-hanging fruit for complete decarbonization — due to the diversity of low-carbon options available — but even here the world is not on track. Today, zero-carbon sources provide 36% of global electricity generation, roughly the same share as it was 30 years ago (BP 2020), despite huge investment in renewable energy (UN Environment Program 2020).

Because of its historic role in decarbonizing energy systems while also providing large-scale, baseload power, nuclear energy has gained renewed support as a tool for climate change mitigation. For that reason, the IEA and NEA (2015) argues that global nuclear capacity needs to double by 2050 to meet aggressive decarbonization targets. Yet global electricity generation from nuclear energy peaked in 2006 and the share of global electricity coming from nuclear has declined from 18% in 1996 to 10% in 2018. Total generation has also remained relatively flat for the last 20 years (BP 2020).

In the last two decades, nuclear power has seen a geographic shift. New builds have stagnated in the West, while Russia, China, and South Korea all have reactors under construction domestically, along with a growing number of export projects and bilateral agreements on technological cooperation (IAEA 2020; Global Nexus Initiative 2017). In addition, over 30 countries around the world are pursuing their first commercial nuclear power plants, so-called nuclear newcomers, many in the global south and almost all will import their first reactors. Historically, the U.S. played an important role in international nuclear security regimes. It leveraged its dominant position in the global market for commercial nuclear power reactors, research reactors, and fuel to require stricter nuclear security and non-proliferation standards in host countries, as well as influencing the standards and norms established by international organizations.

This position is now being undermined by the decline in U.S. nuclear exports over the last four decades, in parallel with a decline of the domestic industry. In the U.S., nuclear energy peaked as a share of electricity generation in 2001 at 20.3% (BP 2020), and with 9 reactors at 7 plants expected to close over the next five years (EIA 2019), that share will likely fall even further. This development and its implications for proliferation control has raised growing concern in security communities (Wallace, Kotek, et al. 2013; Wallace, Roma, and Desai 2018; Ichord 2018). Specifically, the concern is that those countries now exporting nuclear technologies - namely Russia and China - will not hold host countries to as strict security standards.

Exporting conventional, large light-water reactors (LWRs) does not appear to be a promising avenue for regaining U.S. influence abroad. Reactors of this type built in the

70s and 80s in the U.S. were very expensive and took close to a decade to build (Lovering, Yip, and Nordhaus 2016). The recent experience with two reactors under construction in Georgia and the mothballed partially completed plant in South Carolina is repeating this history. Without high and sustained demand, and without a state-supported nuclear industry, the U.S. will struggle to complete such large projects on-time and on-budget, both domestically and abroad. Additionally, such large and expensive power plants are having difficulty competing in deregulated power markets around the world.

The lack of success with large LWRs is one of the main drivers of a move within the nuclear industry toward much smaller nuclear technologies, specifically Small Modular Reactors (SMRs) less than 300MWe and a subcategory called microreactors that are less than 10MWe. There is an expectation that the U.S. is more capable of producing technologies, even complex ones, in a factory setting, given the successes with, for example, Boeing 787s or combined-cycle gas turbines. Furthermore, smaller nuclear technologies, because of their ability to be added to grids incrementally, could be a better fit for liberalized power markets.

When it comes to SMRs and microreactors, the US may hold a leading position. The U.S. currently hosts over 60 companies working on advanced nuclear technologies, including modular designs aiming for full factory fabrication and microreactors small enough to fit into a standard shipping container (Milko, Kempfer, and Allen 2019). While these technologies are not yet ready for commercial markets, most developers are aiming for a commercial product that is significantly less expensive and faster to build than traditional nuclear power plants. If costs can be contained, these new, smaller reactors have the potential to disrupt the global market and strengthen U.S. influence in newcomer countries through expanded exports.

These novel nuclear technologies still face barriers. They will likely need to be licensed and demonstrated in the U.S. first, and past studies have suggested that could take decades and cost billions of dollars (Secretary of Energy Advisory Board 2016). Furthermore, The U.S. government has not been investing nearly enough to commercialize advanced reactor technologies (Abdulla et al. 2017). For this reason, microreactor developers are looking to demonstrate first in niche markets where electricity prices are currently high and the need for reliable power is great.

In many regards, microreactors are moving faster than expected toward licensing and demonstration. In the U.S., the first non-LWR reactor to submit its Combined Operating License (COLA) application to the Nuclear Regulatory Commission (in March of 2020) was a 1.5MWe microreactor (Nuclear Regulatory Commission 2020b), which has received no federal funding. In April 2019, the Canadian Nuclear Safety Commission received their first license application for a microreactor (5MWe), planned for deployment at the Canadian Nuclear Laboratory's site in Chalk River, northwest of Ottawa (World Nuclear News 2019).

Microreactors may prove a more attractive option for meeting the twin goals of revitalizing U.S. exports to strengthen international security and accelerating the deployment of low-carbon electricity. Because of their small size, microreactors could be faster to license, faster and less expensive to demonstrate, and could provide critical power for certain niche markets. Once proven in the U.S., microreactors may be a marketable export product to smaller countries with less developed grid infrastructure. Microreactors also may have some security and non-proliferation benefits including lifetime (sealed) cores, no onsite fuel handling, and remote monitoring. They could also facilitate business models like Build-Own-Operate-Remove or fuel take-back programs.

Significant questions remain around the potential for small and microreactors to scale to the magnitude required to revitalize the US industry and meet global climate mitigation targets. Perhaps the most important question concerns cost; there is a continuing assumption that small nuclear reactors will be too expensive to be competitive for most applications. For example, Froese, Kunz, and Ramana (2020) uses a standard engineering scaling equation to estimate that a 3MW microreactor would cost over $130,000/kW. Similarly, Moore (2016) uses the same scaling equation to estimate that the capital cost of a 10MW microreactor would be over $35,000/kW. Even for a First-of-a-Kind (FOAK) reactor, such costs would be prohibitively expensive in virtually all commercial applications. However, all of these studies are based on the old model of very large nuclear power plants, and none have specifically looked at factory-fabricated small and microreactors.

This thesis investigates two important questions for the future of the nuclear industry. First, what are the implications of a shift away from the U.S. as a leading nuclear exporter? Second, can microreactors be cost-competitive domestically and as a future export product?

Chapter 2 explores the role that nuclear exports have played historically in strengthening international nuclear material control regimes, and the implications of a decline in U.S. exports. I present results from a participatory expert workshop that evaluated policies that might be adopted to regain U.S. influence, including expanded U.S. exports of new nuclear technologies. In chapter 3, I perform a series of techno-economic evaluations of microreactors for community microgrids in order to understand if microreactors can be cost-effectively demonstrated in niche markets. Specifically, I develop case studies for potential first markets including two off-grid diesel-powered Canadian communities, a large hospital in Alaska, and a college campus in Wisconsin.

Whether microreactors can be a marketable export product will ultimately depend on their cost. In Chapter 4, I examine the hypothetical trade-offs between economies of scale and economies of volume for potential factory-fabricated microreactors. I also calculate the break-even volumes necessary for microreactors to become cost-competitive with large reactors and with fossil fuels, using parameters from historic nuclear builds and analogous energy technologies. Finally, I outline some of the policy challenges of this new nuclear paradigm, along with areas for future study regarding the near-term deployment of microreactors.

Chapter 2

Expert Assessments of Strategies to Enhance Global Nuclear Security

Abstract
Historically, the U.S. has sought to use commercial trade in nuclear technologies to influence international nuclear security standards and promote nonproliferation. Concern has grown that, with a stagnating domestic nuclear industry and declining export industry, the U.S. will lose a significant tool of foreign policy and leverage in maintaining strong international standards. While the issue has been discussed extensively in the policy community and used as a powerful rhetorical tool to motivate tangentially related policies such as subsidizing existing U.S. nuclear plants, no one has systematically assessed the issue, structured the problem and proposed and evaluated potential solutions. Here we briefly analyze the current international state of play, and then outline a set of specific strategies the U.S. might adopt on its own, or promote internationally, to retain its influence. Building on the literature, nuclear security and nuclear power experts assisted us in framing the issues and then, in a participatory workshop, helped us to assess and refine possible strategies. While not all experts agreed that U.S. influence has already declined, most indicated that it likely would decline in the future if present domestic and international trends continue. Although none of the proposed strategies that we advanced or that the experts suggested are likely to be effective in the short term, several warrant ongoing refinements and, if they can be implemented, might have beneficial impacts in coming decades.

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2.1 Introduction

Historically, the U.S. has sought to influence nuclear security standards in other nations by striking an elementary bargain: in exchange for providing access to superior commercial nuclear technologies, the U.S. would demand and expect adherence to strict security standards and international safeguards on the use of these technologies. By doing this, the country would not only deepen its economic and geopolitical influence, but also strengthen multilateral regimes that it developed and supported (Blackwill and Carnesale 1993; R. Boardman and Keeley 1983; Wallace, Kotek, et al. 2013).

Recent political controversies around uranium enrichment in Iran and reprocessing rights in Saudi Arabia illustrate how, while often unsuccessful, the U.S. government still seeks to play a strong role in controlling access to sensitive nuclear technologies. The Saudi case in particular will be a test of the extent to which the U.S. can influence nuclear security goals among strategic allies with whom no existing nuclear trade exists—allies who could potentially seek technical support elsewhere. The failure of U.S. commercial nuclear suppliers to secure trade agreements with a number of nuclear newcomers could presage a decline in U.S. influence—one that comes at a critical juncture: nearly 40 countries, most of them in the developing world, are currently pursuing new civilian nuclear programs (Jewell 2011).

In recent decades, U.S. dominance as a global exporter of nuclear technologies has waned and the influence of other nations has risen, particularly that of China and South Korea (Ichord 2018). Russia also continues to play a major role in reactor exports, particularly to nuclear newcomers. While many factors help explain this loss of U.S. market share, here we focus on two that have received considerable attention in the literature. First is the U.S. attitude toward industry support. While nuclear exports provide some measure of international influence, U.S. decisions to pursue nuclear power plant projects internationally are made by commercial entities who assume the risk and the responsibility for project execution. The U.S. lacks effective policy measures at the scale required to encourage exports, whereas such policies are common in France, Russia, and South Korea (Bratt 2006; Ichord 2018; Stott 2010; "The world relies on Russia to build its nuclear power plants" 2018; Walker and Lönnroth 1983). The industry's lack of success in exporting reactor systems mirrors its domestic stagnation (Aumeier and Allen 2017); new nuclear construction in the U.S. has been insufficient to replace its retiring fleet, and has now essentially ceased. Support from policy makers has been timid when compared with competitors who have state-owned utilities and state-supported construction firms. Given escalating costs of nuclear power plants, combined with low-cost natural gas and ever cheaper renewables, new nuclear plants can no longer compete in U.S. power markets that, in most of the country, are experiencing little or no growth (Lovering, Yip, and Nordhaus 2016).

A second factor behind the loss of market share is an export control regime that was designed for a time when the U.S. was the primary global supplier of nuclear technology and exerted unilateral controls to prevent the Soviet Union from gaining any advantage from dual-use nuclear technologies and materials (Committee on Science, Security, and Prosperity; Committee on Scientific Communication and National Security; Development, Security, 2009). The geography of both nuclear suppliers and customers has since shifted. Glasgow, Teplinsky, and Markus (2012) have argued that the U.S. export control system puts the industry at a competitive disadvantage, because it is overly complicated, slow, and opaque, and that a simpler more efficient system could achieve similar security benefits. They argue that the current system may drive customers to import from vendors in Russia, Japan, or South Korea, where the approval process is shorter and less uncertain (ibid.).

Fueled by growing anxieties about national decline and the imperative to maintain nuclear security, experts in the nuclear security and advanced nuclear energy communities have argued that the U.S. should look for ways to bolster its influence even as its role as a supplier of nuclear technologies continues to shrink (Energy Futures Initiative 2017; Wallace, Kotek, et al. 2013). Several recent analyses take as given the premise that U.S. decline in this field is an ongoing and urgent problem. Even these, however, do not offer concrete policy recommendations for how to regain influence in nuclear security regimes, given the constraints facing industry and government. The existing literature has not systematically listed potential strategies for maintaining current influence or regaining influence, let alone evaluated these strategies comparatively. Specifically, existing analyses do not explain the relationship, if any, between the level of U.S. vendors' international commercial success and the nation's influence on global nuclear security. Hence, one goal of our study is to characterize the extent to which a consensus exists among experts regarding this relationship. Note that, for simplicity, we follow previous reports in using the single colloquial term "nuclear security," which encompasses physical security, nonproliferation, and safety.

Our objective in this work has been three-fold. First, we analyzed the historic role that nuclear exports have played for the U.S. and other nations, and then evaluated the extent to which there has been a decline in the U.S. nuclear enterprise's international influence. Second, we have conducted an extensive literature review and exploratory interviews with experts to develop six strategies that the U.S. might pursue to strengthen its leadership in international nuclear control regimes. Third, to evaluate the efficacy and feasibility of these strategies and develop others, we organized an expert workshop that brought together senior nuclear security and energy professionals for a highly structured discussion. It is our hope that the results presented here will prompt others to develop additional strategies, stimulate future research, and inform policy priorities.

2.2 Background and Literature Review

From the formation of the International Atomic Energy Agency (IAEA) in 1957 to the signing of the Nuclear Nonproliferation Treaty (NPT) in 1968, the U.S. has played a key role in establishing strong institutions, requiring strict standards, and sharing best practices for nuclear security and nonproliferation (Blackwill and Carnesale 1993). Originally, the U.S. aimed to keep the entire global nuclear industry under international control. This plan, put forward by American diplomats, was rejected by the Soviet Union. In 1953, understanding that the spread of nuclear technology was likely inevitable, U.S. President Dwight D Eisenhower delivered his famous Atoms for Peace speech, in which he sought to make the peaceful promotion of nuclear science contingent on strict controls on nuclear weapons (Eisenhower 1953). Since then, commercial nuclear technology has been developed and transferred across the world in accordance with international frameworks that aim to limit the proliferation of nuclear weapons.

Historically, due to the U.S.'s ability to offer reliable exports of nuclear technology, fuel, and services, it possessed considerable leverage to require stricter nonproliferation standards in its export agreements, often going beyond those enshrined in international frameworks. Article III of the NPT required non-nuclear weapons states to accept safeguards on their nuclear facilities, but lacked detail on how the IAEA would evaluate compliance, resolve disputes, or respond to non-compliance (Energy Futures Initiative 2017). The U.S. thus struck bilateral nuclear trade agreements, called 123 Agreements in reference to Section 123 of the U.S. Atomic Energy Act of 1954 (Kerr and Nikitin 2016). These agreements generally required acceptance of IAEA safeguards along with prohibitions on domestic fuel enrichment and reprocessing, and placed restrictions on fuel and technology re-export (Walker and Lönnroth 1983). By requiring safeguards compliance in these bilateral trade agreements, the

U.S. paved the way for IAEA inspections that to-date have taken place in over 170 countries (Energy Futures Initiative 2017). Until the 1980s, the U.S. dominated the global market for reactor sales and nuclear fuel, affording it significant influence on other countries' nuclear policies, for instance by discouraging reprocessing and breeder reactors (Kramish 1983). U.S. 123 Agreements include consent requirements for any reprocessing, and stricter re-transfer assurances than set out by the multilateral export control regime enshrined by the Nuclear Suppliers Group (Glasgow, Teplinsky, and Markus 2012). For example, in 1978, the U.S. warned Argentina that nuclear cooperation would cease unless they abandoned plans for reprocessing, which they ultimately did. Similar warnings were given to Brazil in the early 1980s (Miller, 2018).

Starting in the 1980s, with the rise of France and Japan as nuclear suppliers, analysts became concerned that economic competition between countries would drive down export control standards, leading to a so-called race-to-the-bottom (Walker and Lönnroth 1983). In addition, U.S. desire to build relationships with specific countries sometimes interfered with nuclear security and nonproliferation goals (Blackwill and Carnesale 1993). For example, President Nixon offered nuclear reactors to Israel and Egypt, even though neither country had signed the NPT and both were located in a volatile region (Kapur 1983). In the early 2000s, the U.S. hoped to gain influence in Asia by signing a nuclear trade deal with India, even though India had yet to sign the NPT. In response, China signed a similar trade agreement with Pakistan (Fuhrmann 2013). Sanctions on nuclear materials and technology can also provide perverse incentives in the longer term, encouraging countries to develop domestic capacities and fuel cycles rather than rely on international trade (Yager 1981).

The perspective of other major nuclear suppliers has differed from that of the U.S. Whereas the U.S. relied on its successful domestic industry to create demand for exports, Canada had largely sought exports to sustain its domestic industry. Canada also explicitly stated two foreign policy objectives for nuclear exports: aiding developing countries in pursuit of economic growth and constraining the spread of communism (Bratt 2006). France sought to export civilian nuclear power almost purely for economic reasons, and was especially reluctant to limit the spread of fuel reprocessing and fast reactors, sectors in which it had market dominance (Lellouche 1983). The United Kingdom's domestic Atomic Power Station Program struggled to build reliable reactors on-budget, and hence struggled to export its gas-cooled technology (Yager 1981). However, the U.K. maintained significant influence through its status as a nuclear weapon state and because of its deep relationship with India (R. Boardman and Keeley 1983). Appendix A.1 provides more detailed histories of nuclear policy in Canada, France and the United Kingdom.

In two studies, the Center for Strategic and International Studies made the case that success of the NPT was a direct result of the dominance of U.S. nuclear technology in the global market (Wallace, Kotek, et al. 2013; Wallace, Roma, and Desai 2018). These studies argued that without a strong commercial industry, U.S. influence in nonproliferation regimes will diminish, and the influence of exporting nations, some of which have arguably less robust nonproliferation records, will grow (Wallace, Kotek, et al. 2013). However, it remains an open question in the literature as to what the U.S. role should be in a post-Cold War nuclear era, and whether commercial exports continue to be an available tool for U.S. influence.

2.3 Methods

2.3.1 Literature Review and Interviews on U.S. Influence

Rather than consider a wide range of multi-lateral strategies whose implementation would require extensive international collaboration, we choose to adopt an incremental approach, focusing in this first study on policies that could be implemented or led by the U.S. We began our analysis with a literature review and a set of expert interviews to understand the connection between commercial nuclear trade and importing nations' security standards. We focused on the shifting geographies of nuclear trade and asked our experts whether and how these could influence security standards. Appendix A.2 lists literature that figured centrally in this initial survey. We also collected data from the IAEA and the International Energy Agency (IEA) in order to identify and analyze trends in the global commercial nuclear market (IAEA 2020; Lovering, King, and Nordhaus 2017; OECD 2019).

We conducted 13 interviews, five of which were with experts from the U.S. Department of State, U.S. Department of Energy, and U.S. Nuclear Regulatory Commission. A further three were with experts from private sector nuclear companies, three with experts from energy policy think tanks and academia, and two with experts from international nuclear agencies (OECD's Nuclear Energy Agency and the IAEA).

2.3.2 Development of Strategies that Might Increase U.S. Influence

Drawing on insights from these interviews and a further literature review, we developed a set of six strategies (Table 2.1) that the U.S. might adopt or promote in order to strengthen international nuclear security standards. Literature that figured centrally in this process is listed in Appendix A.2 in the SI. Rather than consider a broad range of policies to strengthen nonproliferation standards, we chose to focus specifically on strategies that the U.S. could implement to affect change. We chose a mix of policies that varied in their required investment and level of multilateral engagement.

Table 2.1: Summary of six strategies the U.S. might adopt to strengthen international nuclear security standards. Note that several of these strategies are not predicated on any expansion of U.S. exports of civilian nuclear technology. Rationales for each strategy and discussions of their strengths and limitations, including citations to relevant literature, can be found in the complete workbook in Appendix A of the SI.

Export Control Reform	Modernize, reform and update frequently U.S. export control so as enhance U.S. competitiveness.
The NASA Model	Move much of civilian nuclear development out of the DOE National Labs into the private sector (like NASA did with space launch) and have the labs focus on developing and managing the nation's test facilities and performing basic technology-focused research.
Internationalize the Fuel Cycle	Internationalize and centralize the front and back ends of the nuclear fuel cycle.
International Technology Development	Create and fund an international development center for advanced civilian nuclear energy technologies.
Expert Exchanges	Develop and fund a program of international exchanges on civilian nuclear power technologies with leading nuclear nations and rising nuclear states.
Refocus on Diplomacy	Devote primary attention to enhancing U.S. diplomacy and soft power with the goal of maintaining strong international nuclear security norms.

2.3.3 Expert Workshop to Evaluate Strategies

To understand the role of commercial trade in international security and evaluate these strategies, we hosted a highly structured invitational workshop in Washington D.C. on September 26 and 27, 2018. We invited experts from diverse backgrounds and organizations. Of the 21 experts who participated in this workshop, 11 were from academia and think tanks, 5 from government, and 5 from industry. Participants were evenly split in terms of expertise: half had backgrounds in nuclear security and nonproliferation and half had backgrounds in nuclear power. A list of participants is available in Appendix A.3.

In advance of the workshop, we provided participants with a booklet of pre-readings on the U.S. commercial nuclear industry, the status of U.S. influence in global nuclear security, activities in China and Russia, and international nuclear material control regimes. The full list of those readings is provided in Appendix A.4.

We began the workshop with presentations on the current state of the commercial nuclear enterprise in the U.S. and abroad. This was followed by an overview of the international nuclear material control regimes. Many of the participating experts had been, or are now, directly involved in all aspects of these issues–from working in the U.S. Nuclear Regulatory Commission (NRC) or IAEA to negotiating and implementing commercial nuclear exports. The comments they made on each of these presentations helped to frame and enrich the discussions that followed. They also ensured that all experts were evaluating the feasibility and efficacy of strategies that could enhance U.S. influence from the same comprehensive knowledge base.

Before holding detailed discussions of each of the six strategies commenced, we acknowledged that the premises on which the strategies were based are contestable. We presented each of seven premises one at a time (see pp 6-13 in the workbook at the end of Appendix A) and invited extensive discussion and iterative refinement from the experts. We posed these premises in the form of questions, which are listed below:

1. Do you believe that there has in fact been a loss of U.S. influence on nuclear matters, specifically on setting global nuclear safety and security standards?
2. The idea of "loss of status" or "loss of influence" vis-à-vis the international control regimes may seem somewhat nebulous. Do you have any thoughts on how to operationalize this concept so that the arguments made might be more empirically grounded? What metrics or strategies would you suggest?
3. Having spent the morning discussing the adverse impacts of eroding U.S. leadership

in nuclear matters on global nuclear safety and security standards, we'd like your assessment of the extent to which you consider this to be a problem.

4. One of our premises is that over the past half century U.S. influence on the international nuclear control regime has generally been positive and constructive. To what extent do you agree?

5. Another of our premises is that, while perhaps not essential, a vigorous civilian nuclear power industry and export market dramatically increases a country's ability to exercise meaningful influence on the international nuclear control regime. To what extent do you agree?

6. Some analysts have suggested that the size of the U.S. nuclear weapons stockpile and the large amount of resources spent on it and on the nuclear navy will guarantee the U.S. a large and enduring influence over the international nuclear control regime. To what extent do you agree?

We spent an hour discussing these premises. Each prompted clarifying questions and discussion, again, substantially enriched by commentary and arguments that participating experts drew on from their first-hand experiences. After the discussion of each proposition, we asked the experts to individually judge their degree of agreement or disagreement by marking—or indicating a range—on a linear scale in their workbooks. We also asked each expert to individually provide comments in their workbook on each question and on the general discussion that followed.

The afternoon of the first day consisted of six sessions in which we sequentially considered each of the candidate strategies summarized in Table 1. Each strategy was described in 3 to 4 pages of the workbook. These sections described the proposal, discussed its rationale, and listed the challenges each was likely to face (see pp 13-52 of the workbook in SI). In each case, we began with a general group discussion to elaborate the strategy and eliminate any ambiguities, and then asked participants to complete a number of tasks in their workbook, beginning with an assessment of the likely efficacy of the strategy in 5 and 15 years. Experts did this by allocating 100 points across three possible outcomes if the strategy were adopted: decline in U.S. influence, no change in U.S. influence, and an increase in U.S. influence. For three of the strategies, we provided a list of discrete sub-strategies, and we asked participants to rank their choices for the top three most and least effective sub-strategies. Finally, we provided an open-ended response section in which experts could record their comments on the potential benefits and risks associated with each strategy or suggest modifications to it.

In addition to efficacy, the workbook asked participants to evaluate the feasibility of implementing each strategy in the U.S. by judging the probability that it could be implemented in the next 5 and 15 years, with p=0 being impossible and p=1 being certain. We also asked experts to recommend combinations of strategies that would complement one another if adopted jointly. We left space in the workbook for experts to elaborate suggestions for future work we should undertake and provide broader closing comments.

On the second day of the workshop, we elicited and developed additional strategies that could enhance U.S. influence in international nuclear control regimes. After suggesting a number of strategies, experts focused on four that were discrete and sufficiently different from our original six to warrant further investigation. These were: 1) a U.S. led non-profit consulting firm to provide support to newcomer countries; 2) a domestic solution for nuclear waste in the U.S.; 3) a renewed effort focused on global nuclear disarmament; and 4) a U.S.-South Korea consortium to competitively bid for new reactor construction in newcomer countries. Rationales for each of these four strategies are provided in Appendix A.5. Two weeks after the workshop, we e-mailed our experts a follow-up survey that asked for their judgments of the efficacy and feasibility of these four new strategies in the same way as we had asked with the original six.

Beyond aggregating quantitative assessments of the efficacy and feasibility of each strategy, we evaluated the qualitative and quantitative responses with three additional methods: qualitative coding of open-ended booklet responses, cluster analysis, and correlation checks between all questions. We also checked if quantitative answer were significantly different between the two groups of respondents: energy and security experts. Due to the large number of questions we tested for statistical difference, we applied a Bonferroni correction for the level of statistical significance, which raises the significance level required in proportion to the number of null hypothesis tested (Haynes 2013). Using this correction, we found no significant difference between any of the responses of the nuclear energy and security experts.

2.4 Results and Discussion

Based on our initial interviews and literature review, in section 4.1, we present three models to describe why nations pursue commercial nuclear exports and expound on the historical and current state of U.S. export activities and its influence on nuclear security. Section 4.2 presents results from our workshop. The experts who participated agreed that the U.S. would likely experience declining influence going forward, but disagreed on whether the decline had started and whether policies could or should be adopted to prevent it. A few of the proposed policies were evaluated to be low-risk, high-reward policies, and experts agreed that those warranted further study—we discuss these in section 4.3.

2.4.1 Results from Initial Interviews and Literature Review

Our literature review and initial set of interviews suggested that countries use commercial nuclear exports in pursuit of three objectives: 1) as a point of leverage to strengthen foreign nuclear security standards, 2) as a vehicle for broader political influence and relationship building with strategic allies, or 3) for straight-forward economic benefits. In Nuclear Exports and World Politics (1983), Boardman and Keeley argue that commercial nuclear trade has played a significant role in spreading nuclear technology, but was also the primary mechanism of control of nuclear materials under the non-proliferation regime. An analysis by Fuhrmann (2009) found broader geostrategic objectives for nuclear suppliers entering the global nuclear market including strengthening alliances, strengthening relationships with enemies of enemies (particularly during the Cold War), and strengthening existing democracies. Desires to support domestic industry appear to have played a secondary role in their motivation. However, Lantis (2014) looked at more recent trade agreements with Jordan and Vietnam and found that economic motivations were at least equal to geostrategic motivations in successful nuclear cooperation agreements. One notable difference between the U.S. and other major nuclear vendors is that the U.S. requires that a bilateral trade agreement be in place before any sort of cooperation between countries can take place, not just one that involves exports (Glasgow, Teplinsky, and Markus 2012).

Recent administrations have highlighted the important role that nuclear trade plays by giving the U.S. insight and influence into the capabilities and domestic nuclear policies of foreign nations, although experts have warned that this model is no longer tenable when the U.S. does not have technology that is competitive on the global market (Wallace, Kotek, et al. 2013).

At the same time, and by almost any metric, the U.S. commercial nuclear industry is on the decline. Of the 54 reactors under construction worldwide, only two are in the U.S. (IAEA 2020). Nuclear patents from the U.S. have also been on the decline, averaging over 100 nuclear patents per year from 1960-2000, but falling to less than 20 per year in the last decade. In contrast, patenting in China has grown from almost none in the 1990s, to over 200 per year in the last decade (Lovering, King, and Nordhaus 2017). Even when a country is successfully building nuclear power plants at home, poor technological and economic performance can limit export opportunities, as illustrated by the experience of Canada and the U.K. (Bratt 2006; Yager 1981).

Figure 2-1 shows how reactor export volume from the five largest suppliers (Canada, France, Korea, Russia and the U.S.) shifted between 1960 and 2010. Note the dramatic decline in U.S. exports between 1970 and 2010. Figure 2-2 shows the cumulative destination of reactor exports from Canada, Russia, and the U.S between $1950-2018$. While it has now essentially stopped reactor exports, the U.S. was the largest supplier of commercial reactors over the past 70 years (if Russian exports to republics in the U.S.S.R. are excluded). The U.S. also exported nuclear technology to a more diverse set of countries than anyone else.

Influence rarely ceases once a technology is exported, and U.S. exports generally came with re-export restrictions and consent agreements. Indeed, the U.S., has been able to retain some influence on how technology has been used by foreign countries for decades after the technology's acquisition if it's based on U.S. intellectual property. For example, South Korea's reactor, the APR1400, is based on U.S. technology, and when South Korea exported four of these to the United Arab Emirates (UAE), they could only do so once the U.S. signed a 123 Agreement with the UAE, prohibiting domestic enrichment and reprocessing in the latter. Similarly, until 1982 Westinghouse had an equal share in France's nuclear supplier Framatome, whose reactor was based on a Westinghouse design. France had to obtain U.S. approval before exporting nuclear technology to China in 1979 (R. Boardman and Keeley

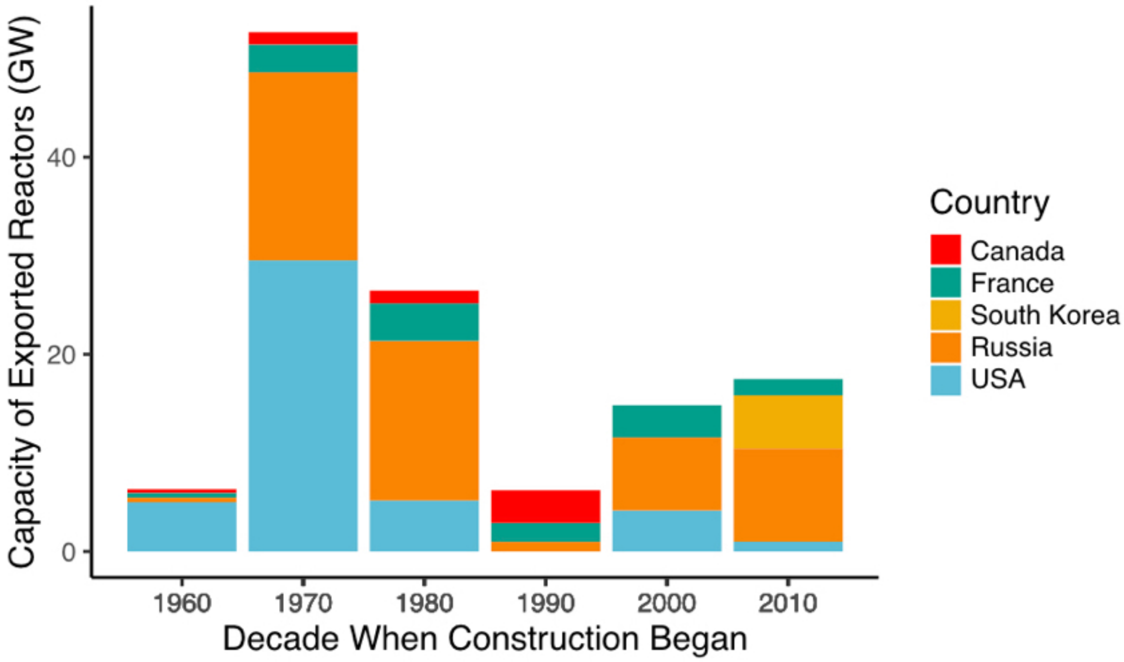

Figure 2-1: Total capacity in Gigawatts of nuclear reactors exported by country and over time, derived from the IAEA's Power Reactor Information System database of commercial reactors (IAEA, 2019). Total exports follow the boom and bust of the global industry as a whole, but the U.S. does not maintain its dominance in the recent revival, whereas Russia does. The emergence of South Korea as a significant exporter is also evident.

1983). The trend in U.S. loss of influence extends beyond reactors to reactor fuel. Until the late 1970s, the U.S. dominated global nuclear fuel supply, with even its main competitors, France and Germany, importing enriched fuel from the U.S. (Yager 1981). By 1994, the U.S. only supplied 30% of the global export market for enriched uranium, and by 2008 that share had fallen to 10% (Wallace, Kotek, et al. 2013).

While it may be optimistic, the IEA projects that the global installed capacity of civilian nuclear capacity will need to double by 2050 to meet aggressive climate mitigation targets (International Energy Agency 2015). Current trends in nuclear cooperation agreements and planned reactors suggest that China and Russia will dominate most new construction (Wallace, Kotek, et al. 2013). Through nuclear agreements, financing, and reactor construction,

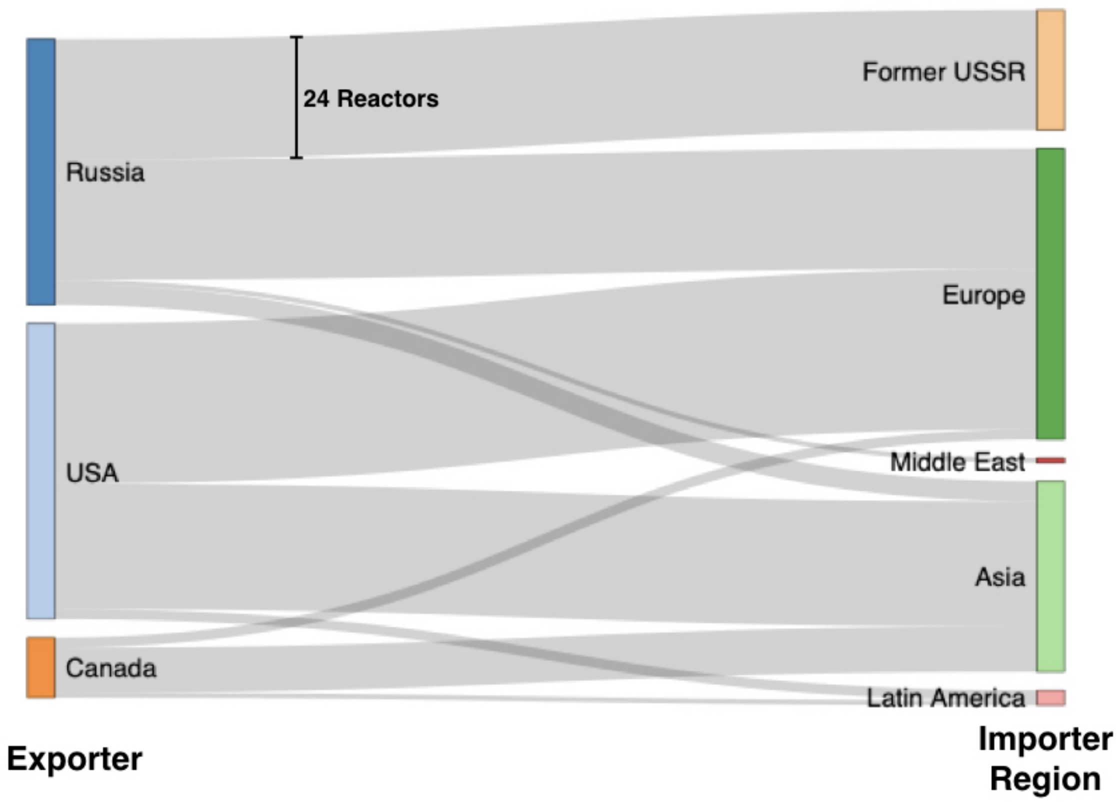

Figure 2-2: The cumulative flow of commercial reactor exports from Russia, Canada, and the U.S., the three largest suppliers (on the left), between 1950-2018 to key geographic regions (on the right). The width of the bars represents the number of reactors exported from left to right. For example, Russia exported 24 reactors to the former U.S.S.R. Raw data on commercial reactors from the IAEA PRIS database (International Atomic Energy Agency (IAEA), 2018).

China and Russia are developing a physical presence in countries that have significant geostrategic implications for the U.S., including in the Middle East and South Asia (Ichord 2018). In an analysis of bilateral nuclear cooperation agreements between 2000-2015, Russia was involved in 46% of global agreements, more than twice the next two countries (France and the U.S.) combined (Jewell, Vetier, and Garcia-Cabrera 2019), and President Putin has explicitly confirmed that civilian nuclear power plays a significant role in Russia's political influence (Fuhrmann 2013). Russia is a favored partner among newcomer countries as they tend to offer competitive state-supported financing and may also act as the builder, owner, or operator of the new plant (Energy Futures Initiative 2017). China is pursuing a more diverse campaign of influence through its One Belt One Road initiative. China's overseas nuclear ambitions fall broadly into three categories: 1) marketing its domestic Hualong reactor for export, 2) investing in existing nuclear projects, such as Hinkley C in the UK, and 3) partnering with Canada and the U.S. to develop advanced reactor concepts. Additionally, China has invested heavily in nuclear innovation, including developing small modular reactors (SMR), molten salt reactors, and high-temperature gas reactors (Ichord 2018).

This changing global market deprives the U.S. of key engagements with important countries. The Middle East has witnessed growing interest in nuclear power in the last decade, but the U.S. has been unable to conclude bilateral nuclear agreements with Egypt, Jordan, or Saudi Arabia; all three signed agreements with Russia that lacked restrictions on enrichment and reprocessing and also provided generous financial and technical support (Energy Futures Initiative 2017). Of the countries across Africa that are interested in starting commercial nuclear programs, most have nuclear cooperation agreements in place with China or Russia, and some with South Korea. The U.S. historically played a strong role in promoting African nuclear power, but is now notably absent (Sah et al. 2018).

2.4.2 Results from the Workshop: Investigating the Premises

The level of expert agreement on our six arguable premises is shown in Figure 3. While we cannot claim that they are statistically different, we report the responses from security experts and reactor experts separately to illustrate their different views. While the agreement was lower than we expected on the first statement, that the U.S. had lost influence, the experts qualified in their written comments that the U.S. is just starting to lose influence and it will likely decline going forward. From our qualitative coding, we found that those who strongly agreed with this statement were more likely to cite the leading role the U.S. had in IAEA and the previous dominance of U.S. technology. Of those who thought the U.S. had not lost influence, all agreed that exports contributed to influence, and more than half used phrases referring to a "turning point" or "inflection point", suggesting that the decline is only now unfolding.

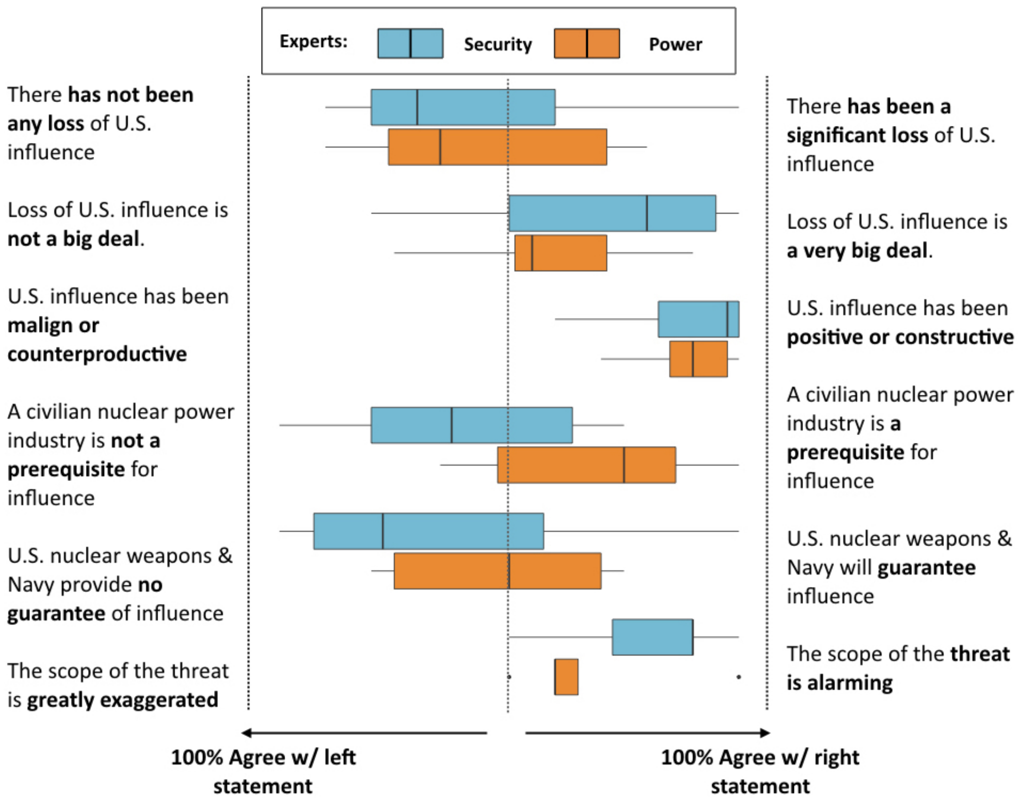

Figure 2-3: Expert level of agreement with six arguable premises that underpinned workshop discussions, separated out by expert background. The six opposing pairs of statements are on the y-axis, with experts marking where between the two statements their agreement lay. The boxes extend to one quartile from the median, the whiskers extend 1.5 times the interquartile range, and the dots show outliers that lie beyond the whiskers. The full wording of these statements can be found in the complete workbook included in Appendix A.

Workshop participant #18 noted, "Our influence is still strong, but is diminished to the extent that new builds are based on foreign designs with foreign licensing." Participant #19 noted that the "U.S. had a major hand in creating [the] IAEA Safeguards system, NPT, NSG [Nuclear Suppliers Group], and all major conventions on safety and security. More than many of the suppliers, [the US] has been willing to enforce nonproliferation through use of political and economic leverage.” Participant #4 detailed a more specific pathway of how the U.S. affects security standards and how that role may be diminished, “IAEA relies heavily on expertise from [the] U.S., based on exporting past [light-water reactor] technologies. If [the] U.S. is not a player in advanced technologies, [it] won’t have the expertise to supply [to] IAEA.” There was broad agreement that U.S. influence would wane as countries began deploying advanced, non-light-water reactor technology that had not been commercialized first in the U.S.

The security experts agreed to a greater extent than the energy experts that loss of influence was a concern, and that breaches of nuclear security and proliferation posed significant risks. Participant #7 wrote, “The U.S. has had an enormous positive impact on safety through its international programs and work with IAEA. On security, the U.S. has taken lead responsibility in general and in crises, e.g. securing materials during the collapse of the USSR. Likewise, it has taken the lead on conversion of research reactors around the world.” Agreement was high among experts on the assumption that the U.S. has played a predominantly positive and constructive role. The most frequent comments associated with this question related to the role that the U.S. played in the IAEA and NPT.

Unsurprisingly, nuclear energy experts agreed more with the statement that a robust commercial industry is a prerequisite for U.S. influence, while nuclear security experts were skeptical of the link between the two issues. Participant #17 wrote, “We should not prop up U.S. industry simply to achieve influence.” That said, nuclear security experts who declared that a commercial industry was not a prerequisite for international influence agreed that it nonetheless had its benefits. Participant #3 argued, “Even with no nuclear capacity, the U.S. would have other tools in its toolkit to influence the behavior of other states. What is at risk though is the diminishment of targeted forms of influence that will result in the U.S. needing to use blunter instruments that will be more controversial as the effects will be less targeted and thus harder to defend. It's one less arrow in the foreign policy quiver and a very big one at that." In the past, the U.S. government invested significantly more resources in promoting nuclear exports than it does today. While our experts thought that higher levels of U.S. investment could be useful, they questioned whether doing that would have the same efficacy today in strengthening US influence, without a correspondingly strong demand from domestic and export markets. The workshop discussion also clarified the fact that the U.S. government does not embark on executing 123 Agreements until a concrete project is proposed between a nation and a U.S. vendor.

2.4.3 Results from the Workshop: Expert Assessments of Strategies

Experts evaluated each of the six strategies for both their potential efficacy if each was implemented, and for their feasibility in the next 5 and 15 years. The full results can be found in Appendix A.6. Experts evaluated each option by allocating 100 points across three possibilities that could result if it were implemented: 1) that it would lead to an increase in U.S. influence over the time horizon in question; 2) that it would lead to no change in U.S. influence; or 3) that it would lead to a decrease in U.S. influence. In Figure 2-4, we present the results for the 15-year time horizon. Results for the 5-year time horizon can be found in Appendix A.6. Experts' assessments of the sub-strategies for export control reform, internationalization of the fuel cycle, and the NASA model can be found in Appendix A.7.

Two strategies, the NASA model and an internationalization of the fuel cycle, received the highest median score for increasing U.S. influence, although the broad range of responses means that the difference between strategies is not statistically significant. All strategies

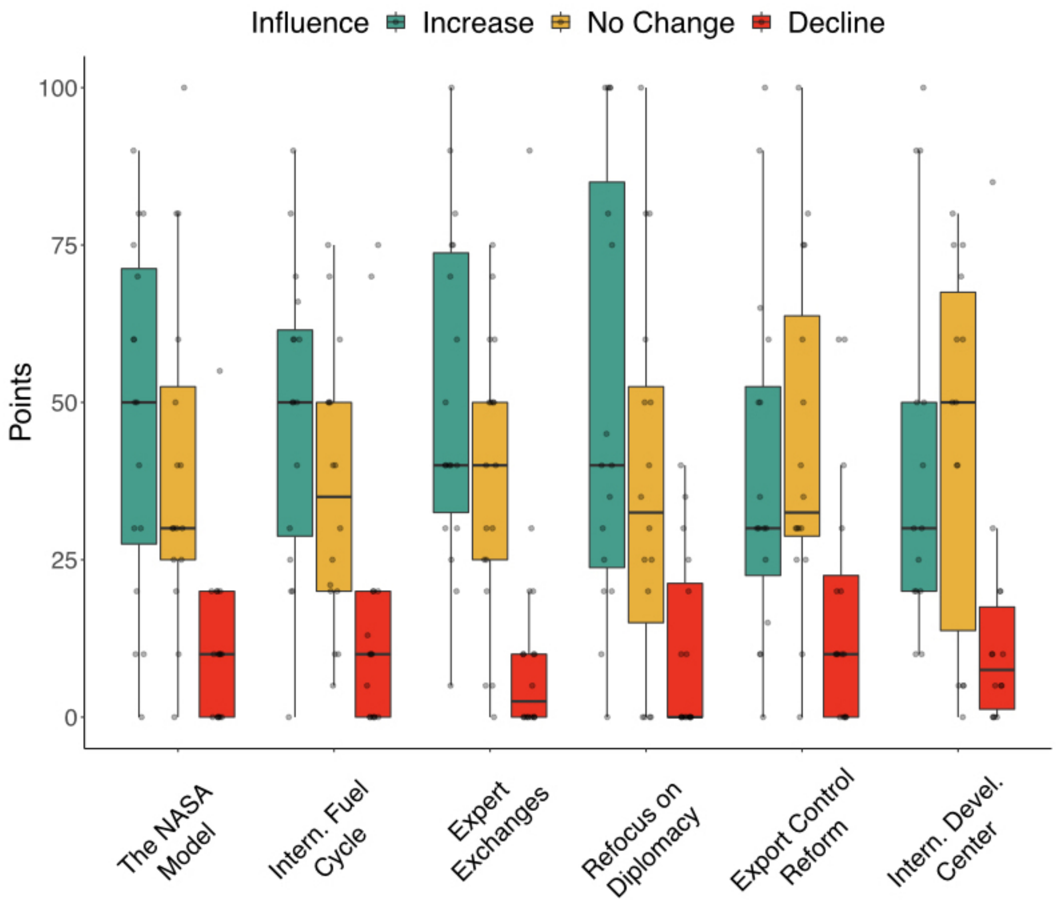

Figure 2-4: In evaluating each strategy, workshop participants allocated 100 points to three outcomes: 1) an increase in U.S. influence (green); 2) no change in U.S. influence (yellow); and 3) and a decline in U.S. influence (red). Individual responses are provided in the SI. The strategies are ordered from left to right by their median "increase in influence" score (in green). Boxes extend one quartile from the median; whiskers extend 1.5 times the interquartile range; and dots show individual responses. The strategies on export control reform, internationalizing the fuel cycle, and the NASA model included sub-elements which the experts ranked in terms of which could be "most useful" and which were "bad ideas." Results from those rankings are provided in Appendix A.7.

were judged to be broadly positive. In other words, if adopted they would not lead to a decline in U.S. influence. The diplomatic strategies received the lowest median rating for a decline of influence. Two outlying responses suggesting a decline in influence were made by the same respondents. From their written comments, it is clear that the first considered the decline of U.S. influence inevitable regardless of U.S. actions. The second expected U.S. influence to be attenuated by loss of U.S. intellectual property regardless of actions.

Beyond quantitative evaluations, our experts provided written comments on each strategy, and we elaborate some of their arguments here. For export control reform, a few security experts were concerned about a "race to the bottom" where controls would be loosened to buttress nuclear exports. On the other hand, a few industry experts were worried that export controls would get stricter. That said, three comments made by the experts highlighted that the U.S. was at a turning point with respect to advanced nuclear designs and the role of export control in negotiating this turning point. First, five experts made some form of the argument that, if other countries turn away from U.S. designs, America's ability "to influence safety and security standards [would be] diminished. This will be particularly the case for advanced reactors that are initially licensed by a foreign regulator" (Participant #18). Not only that, but "it is likely that a newcomer country, particularly one without prior experience with nuclear [power], will build its regulatory system on the foreign model—not on the U.S. model" (Participant #18). In summary, continued U.S. stagnation on the advanced reactor front will mean that "foreign approaches will largely prevail by default. To the extent [that light water reactors continue to be built], there could be some lingering role for the U.S. model" (Participant #18).

For both collaborative strategies—involving expert exchanges and creating an international technology development center— participants expressed concern that the government would simply be "spending U.S. funds to help other countries become more competitive and technologically advanced" (Participant #7). The NASA model, while attractive, raised concerns among a few of the energy experts that government money would not be spent efficiently, and that more policy was needed to stimulate market demand for these technologies.

Almost all of the experts agreed that internationalizing the fuel cycle would enhance global nuclear security, partly by increasing the stringency associated with enrichment activities and foreclosing national enrichment program. However, this strategy was rated lowest in terms of feasibility, and over half of the experts expressed doubts that this was a feasible strategy to pursue for a country that has now largely exited the fuel market, as the U.S. has. The investment and effort required for the U.S. to restart a robust domestic fuel industry was too large; as Participant #14 succinctly noted, “it’s not clear that the juice is worth the squeeze.”

Spearheading an international advanced reactor development center makes sense only when the technical readiness of the system is sufficiently low, or the work sufficiently generic, that collaborative research does not infringe upon commercial propriety. Despite these reservations, our experts recommended a collaborative research institute that focused on making advances in safety, security, and safeguards. Participant #14 argued that, “properly implemented, [such a center] could [weaken] arguments for national enrichment and/or research programs on grounds of security of supply, [thus] reinforc[ing the] reliability of [the] current global market.”

Despite their appeal and the existence of previous models of successful expert exchanges such as the Pugwash Conferences (Robinson, 1998), there was virtually universal concern regarding their impact on intellectual property. For this reason, the experts suggested that the exchanges focus on safety, security, and safeguards in order to lower the risk of theft of intellectual property and leverage U.S. expertise in these fields. Almost everyone agreed that investing more in diplomacy was a good idea, regardless of the implementation status of other strategies.

Figure 5 displays expert evaluations of each strategy’s feasibility over 5- and 15-year periods. Differences in median feasibility are statistically significant for some comparisons: over the 5-year time period, the feasibility of Expert Exchanges was deemed significantly higher than that of the NASA Model, the Internationalization of the Fuel Cycle, and the International Development Center. Over a 15-year time period, the feasibility of Export Control Reform was deemed significantly higher than that of the Internationalization of the Fuel Cycle and the International Development Center. Moreover, over a 15-year period, both a Refocus on Diplomacy and Expert Exchanges were deemed more feasible than the NASA Model, the Internationalization of the Fuel Cycle, and the International Development Center. The most significant change in the feasibility of a strategy between the 5 and 15-year time periods is for a Refocus on Diplomacy, which increases from a median of 0.1 to 0.9, reflecting pessimism about the current state of U.S. diplomacy and a glimmer of hope for future corrective action. That said, the range of responses is quite broad for both periods and different between security and energy experts. For the Expert Exchanges, the median feasibility rose from 30% to 70% when moving from the 5-year to the 15-year time horizon. However, for security experts, assessments remained at 50% for both 5- and 15-years. When evaluating the feasibility of Refocusing on Diplomacy, the power experts increased their evaluation from 10% to 50% when looking at longer time horizons, and the security experts went from 50% to 90%.

Knowing that our six proposed strategies represented a limited set of interventions, and potentially not the best ones, we asked participants during the second day of the workshop to identify and elaborate their own sets of policies that might be used to enhance U.S. influence. Four discrete strategies were developed over the course of the discussion. These were presented to experts in a follow-up survey, where they were asked to evaluate them in an identical manner to the original six strategies.

The first expert-derived strategy was to develop a **Non-Profit Consulting Firm** to aid

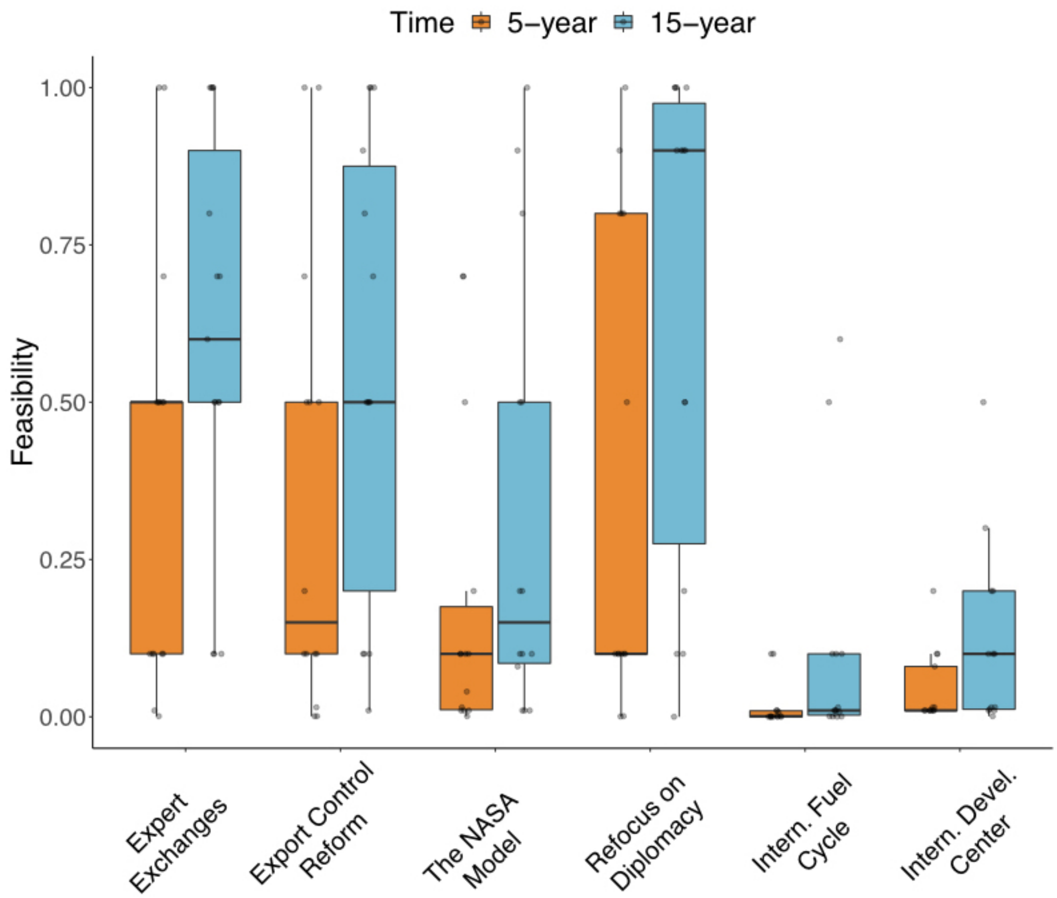

Figure 2-5: Expert assessments of the feasibility of each strategy over 5- and 15-year time periods, which is defined as the probability that each strategy could be implemented. Boxes extend to one quartile from the median; whiskers extend 1.5 times the interquartile range; dots show individual responses.

and advise newcomer countries embarking on their first commercial nuclear power projects. This entity would go beyond the advice offered by standard IAEA visits, and could include analytical and other help in reviewing commercial proposals. The goal would be to develop a non-governmental organization (NGO) that possesses credibility and objectivity, while leveraging U.S. expertise.

The second was to revivify efforts to make **real progress on nuclear disarmament**, in fulfillment of legal obligations enshrined in the NPT. Experts argued that lack of progress on disarmament weakens U.S. standing in international safeguards negotiations, particularly with Russia, but also with non-aligned states. The strategy could also include a push to ratify the Comprehensive Test Ban Treaty.

The third strategy was to renew efforts to develop a **domestic solution for nuclear waste**, which retains the option of taking back waste from customer nations in the future. This would restore U.S. reputation and help level the playing field with Russia's take-back programs. Most likely, this process would have to rely, at least in the short-term, on the Department of Energy's consent-based approach to siting regional interim storage facilities until a policy window opens for long-term disposal.

The fourth and final expert-derived strategy was to develop a **U.S.-South Korea Construction Consortium** to build nuclear power plants, either in the U.S. or in third countries (Mcgoldrick et al. 2015). Joint construction in newcomer countries would appear to have the most leverage in influencing security standards. This approach would merge Korean nuclear construction experience with the diplomatic heft and industrial base of the U.S.

Results from the follow-up survey are shown in Figure 2-6. Following the same structure as the original workbook, participants allocated 100 points across three outcomes for each strategy over both 5 and 15-year time horizons. The three possible outcomes of implementing each strategy include an increase in U.S. influence, no change in U.S. influence, or a decline in U.S. influence. The results for the 5-year time horizon are included in Appendix A.6, with the main trend being that all strategies become more effective and more feasible over the longer time horizon. The experts also evaluated the feasibility of each strategy over 5 and 15-year time horizons. There appears to be an inverse relationship between the likelihood that a strategy will increase U.S. influence and its feasibility. Experts thought that a renewed push for national disarmament would significantly enhance U.S. reputation on nonproliferation issues. Over three-quarters of respondents thought that a U.S.-South Korea construction consortium would be a pragmatic way to re-establish U.S. presence in the global nuclear market; at least three experts were more reticent, arguing that Korea would gain more from the partnership than the U.S.

Finally, we performed a clustering analysis based upon all of the quantitative responses in the workbook. We employed the CLARA package in R, which minimizes the Euclidean distances between expert responses. Clustering into four groups yielded the lowest standard error. The first cluster contained six experts who strongly agreed that the U.S. had lost influence and that the commercial sector was a source of influence. They also tended to be rather pessimistic about the effect of any strategies on U.S. influence. While they ascribed low likelihoods to the notion that any strategy would decrease U.S. influence, they ascribed high likelihood to the notion that strategies would result in no change in U.S. influence. The second cluster contained three experts who also strongly agreed that the U.S. had lost influence, but strongly disagreed that a robust U.S. commercial nuclear industry would enhance or guarantee influence. Their judgments coalesce around the notion that the existence of U.S. nuclear weapons and U.S. Navy nuclear propulsion guarantee influence. While members of the first cluster could be regarded as pessimists, members of the second cluster were focused on defense. The third cluster contained most of the experts from the nuclear and electric power industry. Unsurprisingly, these experts rated Export Control Reform as likely to increase U.S. influence. The fourth cluster contained three experts who disagreed that the U.S. had lost influence, but also believed that a robust commercial industry was a prerequisite for influence. In addition, they deemed both the Expert Exchanges and the International Technology Development strategies as having high likelihoods of decreasing U.S. influence, most likely due to the transfer of U.S. intellectual property to other nations that they believed these two strategies entail.

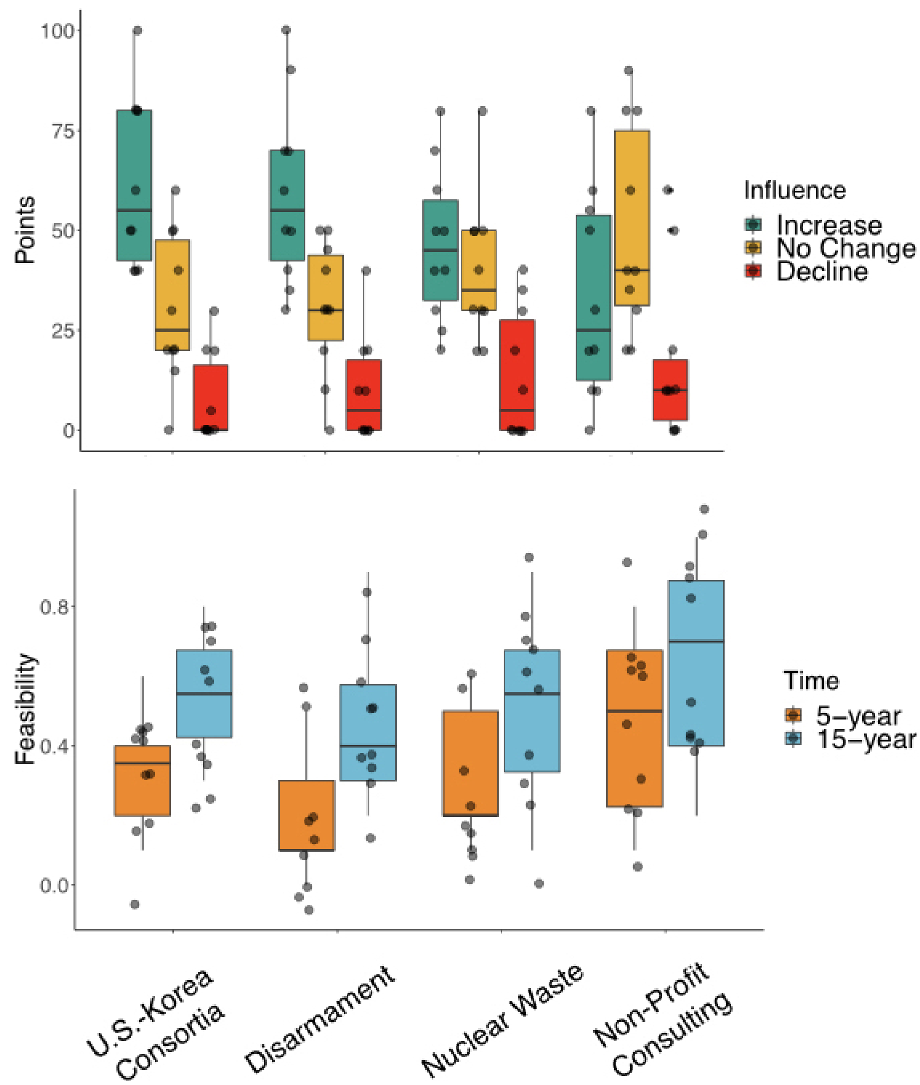

Figure 2-6: Expert assessments of the efficacy and feasibility of four strategies. The top chart shows the efficacy of each scenario over a 15-year time horizon, defined as the probability that each strategy will increase U.S. influence. The bottom chart shows feasibility, defined as the probability that each strategy could be implemented. Boxes extend to one quartile from the median; whiskers extend 1.5 times the interquartile range; dots show individual responses.

Figure 2-7 compares the expert-evaluated efficacy and feasibility of all ten strategies over the 15-year horizon; they can be broadly categorized as falling above or below the median for each metric (Appendix A.6 contains results for the 5-year time horizon). Experts assessed

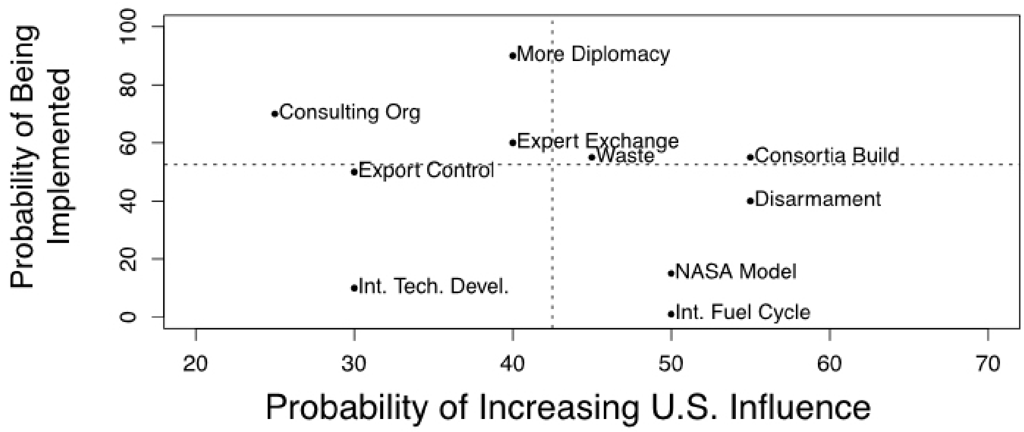

Figure 2-7: Categorization of strategies based on expert assessments of their efficacy and feasibility over a 15-year time horizon. Dotted lines show the median of the expert evaluations for each metric.

the U.S.-South Korea construction consortium and progress on nuclear waste to be relatively more feasible and more effective, which allows us to investigate these two strategies in greater depth in future work. In contrast, strategies that are deemed effective but infeasible should be investigated in more depth to determine whether they could be gradually or partially implemented—whether the juice is worth the squeeze, to recall the words of one expert.

2.5 Conclusions and Policy Implications

Experts who participated in the workshop broadly agreed that, in the past, the strength of the U.S. commercial nuclear industry played a significant role in facilitating U.S. leadership in international control regimes. They also believed that, with diminished presence in civilian nuclear power, U.S. influence with respect to these regimes is likely to decline—particularly for the next generation of nuclear technologies. However, the experts did not agree on whether U.S. influence had already declined.

When asked to evaluate the efficacy and feasibility of six proposed strategies to enhance U.S. influence internationally, along with four additional strategies the experts had developed during the workshop, two strategies emerged as above median feasibility and efficacy over the next 15 years: the creation of a U.S.-South Korea Consortium to build new power projects and progress on addressing the problem of U.S. domestic nuclear waste. Progress on nuclear disarmament, adoption of a NASA Model involving support for private reactor developers, and internationalizing the nuclear fuel cycle were assessed to be highly effective strategies that are also unlikely to be implemented. The efficacy of the two diplomatic strategies was deemed below average, but their feasibility fell above the median. The lowest ranked strategies in terms of efficacy were developing a U.S.-based consulting organization for countries aspiring to build their first nuclear power plant, reforming the nation's export control system, and building an International Technology Development Center. The latter two also ranked below the median for feasibility, suggesting that policy makers should think carefully before investing heavily in their development and implementation.

While energy and security think tanks have published warnings of declining U.S. influence, the broad range of responses from our experts highlights the fact that better data are needed to define and track this influence and its effect on international nuclear security standards. Some of the ideas coming out of the workshop included mapping the flow of global nuclear trade over time (e.g. through commercial reactor exports, research reactors, trade in fuel, enrichment and reprocessing services) and nuclear cooperation agreements between countries. A more informative but more challenging effort would involve tracing security and nonproliferation outcomes back to nuclear trade. This activity could establish whether customers of certain suppliers subscribe and adhere to stricter security protocols, and whether that commitment is durable. It could also highlight whether, or how often, countries achieved policy goals in international negotiations.

While the issue of U.S. influence has been discussed extensively in the policy community, prior to this study no one in the engineering or policy communities had systematically structured the problem or proposed and assessed potential solutions. Instead, to date the issue has largely been used as a rhetorical tool to motivate tangentially related policies, such as subsidies for existing commercial nuclear power plants. Work to develop and assess additional strategies to strengthen control regimes is clearly and urgently needed.

Chapter 3

Case Studies of Microreactors for Microgrid Applications

Abstract
In the last decade, there has been significant work on the potential of microgrids, both for expanding access energy-poor countries and increasing reliability and resiliency on existing grids in high-income countries. However, most microgrids in the U.S. and Canada today are powered primarily by fossil fuels. Nuclear power has traditionally been too large to be relevant for microgrids, but a new suite of microreactors — Small Modular Reactors (SMRs) under 10MWe — offer a novel opportunity to decarbonize off-grid demand centers. To understand the potential commercial market for microreactors, I performed a techno-economic evaluation of a generic 1MWe microreactor deployed to serve load across several off-grid applications for which I could acquire real hourly electric load data over the course of a year. I used the HOMER software package to optimize microgrids for each community under a range of technological scenarios including diesel, microreactors, renewables and batteries. I looked at results in terms of levelized cost, emissions, and reliability of the system, before performing a sensitivity analysis over all parameters of the microreactor. The results indicate that microreactors could be cheaper and more reliable compared to a 100% renewables systems, and they could also be cost-competitive with diesel in regions with high fuel costs and cold climates.

3.1 Introduction

Global nuclear energy generation has stagnated over the last decade, and will likely decline in North America and Europe over the next decade. Large-scale, conventional nuclear power plants have struggled to be built on-time and on-budget. Yet near-term commercialization of Small Modular Reactors – factory fabricated systems under 300MWe – has renewed interest in nuclear as a potential contributor to global decarbonization. There is already an extensive literature on the potential benefits and challenges of SMRs (Locatelli, Bingham, and Mancini 2014; Vujić et al. 2012).

While there are plans to break ground for the first commercial SMRs in the next few years, another wave of even smaller reactors, so-called microreactors less than 10MWe, are beginning the licensing process and are aiming to deploy their first demonstrations on similar timescales. In the US, six advanced reactor companies have initiated pre-application licensing activities with the Nuclear Regulatory Commission (Nuclear Regulatory Commission 2020a), and the first non-LWR to submit a Combined License Application was a 1.5MWe microreactor from Oklo, Inc. in March of 2020 (Nuclear Regulatory Commission 2020b). In April of 2019, the Canadian Nuclear Safety Commission received their first license application for an SMR design, and it was a 5MWe microreactor, planned for first deployment at the Chalk River Laboratories in Ottawa (World Nuclear News 2019).

Microreactors are not simply smaller SMRs, but represent a step-change in the way nuclear power has historically been deployed. Unique attributes of proposed microreactors include: integrated steam turbine; minimal moving parts in the reactor; transportable by rail or truck; long core lifetimes; and autonomous operation or operation with minimal staffing. Thus, microreactors could open up a whole new market, the microgrid or community-scale market, to nuclear power. For example, a 2019 Nuclear Energy Institute report found that

90% of military installations could meet their annual demand with one or more microreactors.

There has been significant interest from governments in supporting microreactor development, but little study of the techno-economic challenges of commercial applications. In the U.S., funding for advanced nuclear technologies started to increase in the mid-2000s, but only in the last few years have policies made funding available to smaller, private development efforts. DOE's Gateway for Accelerated Innovation in Nuclear (GAIN) program began offering vouchers in 2016 to advanced nuclear developers to access experimental facilities and expertise at national laboratories. Several microreactor developers have been awarded these vouchers. DOE has also awarded small grants for specific research and development projects to several advanced reactor developers. While these grants are for only a few million, they may comprise a large share of these vendors' funding. DOE's Advanced Research Projects Agency-Energy (ARPA-E) nuclear funding program has also been granting money to microreactor developers. The National Reactor Innovation Center (NRIC) was established at Idaho National Laboratories in 2019 with the mission of demonstrating an advanced reactor concept by 2025.

In the last ten years, there have been more policies directed specifically at microreactors. In the U.S., the 2010 National Defense Authorization Act directed the Secretary of Defense to conduct a study on the potential for nuclear power to be deployed at defense installations (U.S. Congress 2009). In September 2018, DOE put out a Request for Information on a pilot program for microreactors, asking for input on what resources would be needed (e.g. regulation, fuel, funding) for private reactor developers to build a micro-reactor at a DOE or DOD site before the end of 2027. Relatedly, the Nuclear Energy Leadership Act (NELA), which passed the Senate Energy and Natural Resources Committee in July 2019, would extend the limit of federal Power Purchase Agreements (PPA) from 10 to 40 years, making it easier for nuclear reactor vendors to compete for federal PPA contracts. NELA also directs the federal government to sign at least one PPA with an advanced reactor vendor before the end of 2023 (U.S. Senate - Energy and Natural Resources 2019). In 2016, Canadian Nuclear Laboratories put out an invitation for SMR developers to submit proposals to build a demonstration reactor at their Chalk River site, with the goal of commissioning before 2026. This has spurred several companies to initiate the pre-licensing, staged vendor design review with CNL (Canadian Nuclear Safety Commission 2020).

Microreactors may be a more appropriate size for defense installations, compared with traditional SMRs, however cost is an even bigger obstacle. On a kilowatt-hour basis, power from microreactors is expected to be more expensive than from larger reactors. The Department of Defense prohibits power purchase agreements that pay above market rates for electricity. Thus, some microreactors developers are seeking other niche markets where customers are already paying significantly higher rates for electricity. One promising candidate is off-grid communities that obtain their power from diesel generators. A 2011 study conducted by the Canadian Government found over 290 off-grid communities, with a collective population of almost 200,000 (Government of Canada 2011). The average fossil-fueled powered generator capacity of these communities was just 1.8MW. A 2015 report commissioned by the Australian Energy Council found over 1000 islanded electricity systems and microgrids across Australia, serving a population of 450,000. Similar to Canada, almost all of these communities are dependent on fossil fuels for their electricity. Australia's off-grid communities are seeing growing penetrations of renewables, but there are significant challenges in maintaining grid stability and reliability with intermittent renewables (Energy Supply Association of Australia 2015).

While nuclear power can technically load-follow, it typically does not do so on large-scale power grids for economic reasons; almost all of nuclear power's costs are fixed (International Atomic Energy Agency 2018). However, on a microgrid, load-following capabilities may be more valuable, especially when balancing renewable energy. Two studies have looked at including nuclear on islanded microgrids (Hong and Brook 2018; Islam and Gabbar 2015), but neither explored load-following. More importantly, both studies employed larger 100MW reactors with fixed levelized cost, not adjusting for load factor or plant lifetime. Therefore, many questions remain unanswered with regard to the potential deployment of microreactors.

This study evaluates how much microreactors need to cost to be competitive with diesel generators at different fuel prices. Further, there is a need to look at how nuclear-based microgrids perform over the course of a whole year compared with fossil and renewable alternatives. To that end, I have modeled how microreactors could meet demand over the course of a year in four case studies based on real-world systems. I acquired historical hourly load data for two off-grid, diesel dependent communities in Canada, a large hospital in Fairbanks, Alaska, and the University of Wisconsin Madison campus. Then, using the HOMER software, I modeled a range of different microgrid scenarios to serve these loads using generation mixes that included diesel, nuclear, renewables, and batteries and optimized each for lowest cost and emissions. I also performed sensitivity analysis for the nuclear and diesel technologies to understand where the cross-over in lowest cost occurs.

3.1.1 Literature Review

One of the primary motivators for studies of nuclear power on microgrids has been interest from the U.S. Department of Defense, for both domestic installations and forward operating bases overseas. The 2010 National Defense Authorization Act directed the Secretary of Energy to conduct a study evaluating the feasibility of deploying nuclear power for military installations (U.S. Congress 2009). Middleton et al. (2016) looked at light-water SMR technologies for U.S. Air Force installations, specifically Schriever Air Force Base in Colorado and Clear Air Force Station in Alaska. They found that near-term SMR technologies were too large and too expensive for most applications, especially since the military is unwilling or incapable of paying for the value of increased reliability and resiliency that might be provided by nuclear systems.

Yet other studies that looked at much microreactors for military applications have found that the technology could be appropriate. Holland (2019) argues that microreactors present a unique opportunity to advance energy reliability and resilience at military installations both domestically and abroad, noting that China and Russia are likely already pursuing this pathway for the technology. More specifically, the author notes that TRISO fuel pebbles offer attractive advantages in terms of density and safety, and that microreactors that use TRISO will have an advantage.

Moving beyond military applications, several government reports have looked at the challenge of providing clean electricity to small, off-grid communities, such as in Canada and Australia (Energy Supply Association of Australia 2015; NT Energy 2013). A 2011 study conducted by the Canadian Government found over 290 off-grid communities with a collective population of almost 200,000 (Government of Canada 2011). The average fossil-fueled power capacity of these communities was just 1.8MWe. A 2015 report commissioned by the Australian Energy Council found over 1000 islanded electricity systems and microgrids across Australia, serving a population of 450,000. Similar to Canada, almost all of these communities are dependent on fossil fuels for their electricity. Australia's off-grid communities are seeing growing penetrations of renewables, but there are significant challenges in maintaining grid stability and reliability with intermittent sources (Energy Supply Association of Australia 2015).

There is an extensive literature looking at various aspects of renewable microgrids -

primarily optimizing for specific sites and combinations of technologies - but I could only find two studies that looked at the potential to include nuclear when modeling islanded microgrids. Islam and Gabbar (2015) calculated the levelized cost of three hypothetical 100MWe microgrids located in Ontario, Canada: using 0% nuclear, 50% nuclear, and 100% nuclear, with the remaining balance coming from wind and solar. They found that the 100% nuclear system had the lowest overall costs, but their cost estimates were not sensitive to real-world parameters such as load factor. Similarly, Hong and Brook (2018) optimized nuclear-renewable microgrids for three island systems: Jeju in South Korea, Tenerife in Spain, and Tasmania in Australia. Using real demand data and generation costs for renewables, they optimized grids for SMRs over a range of generating costs from \$60/MWh to \$120/MWh. They found that nuclear was cost competitive when generating costs were below \$100/MWh. Nuclear needed to be cheaper than fossil alternatives to compete without an explicit limit or price on carbon. However, the study has several short-comings in terms of how they deploy the SMR, mainly that the LCOE is fixed independent of annual generation.

Very few studies have evaluated the use of nuclear on microgrids because previous nuclear technologies have been too big. Even Small Modular Reactors tend to range from 100-300MWe. As a rule of thumb, no single generator should comprise more than 20% of a microgrids capacity, so a nuclear reactor would need to be less than a quarter of a community's peak power needs to make economic sense for deployment. The reasoning for this is resiliency, you want to be able to shut down at least one of your generators at a time for repairs without having to shut down the whole grid system. Until very recently, there were no nuclear systems that were appropriate for off-grid applications. However, as previously noted, in the last five years, there has been a surge of new microreactor designs (Nuclear Energy Institute 2018). A summary of the most mature microreactor designs is provided in Appendix B.1.

3.2 Data and Methods

To evaluate the potential role that microreactors might play in off-grid applications, I acquired hourly electric and thermal load data for a whole year for several example applications: two diesel-dependent communities in Northern Quebec, a large hospital, and a college campus. Hourly electric load data was acquired for two off-grid, diesel-dependent communities in Northern Quebec. Note that I used data from the these locations to provide realistic examples – to my knowledge none have expressed interest in pursuing nuclear power.

I have three years (2013 to 2015) of hourly electric load data for for the two communities. For the hospital case study, I acquired hourly data from the U.S. Department of Energy's catalogue of commercial and residential load profiles. While they have reference hospitals in all major cities, I chose a large hospital in Fairbanks, Alaska for this first analysis. These data have both electric and thermal load information. Lastly, I have a year's worth of electric and thermal load hourly data for the University of Wisconsin Madison. A summary of the data is provided in Table 3.1.

Table 3.1: Details on electricity and thermal demand data collected to date.

Metric	Comm. A	Comm. B	Fairbanks Hospital		UW Campus	
Load Type	Elec.	Elec.	Elec.	Ther.	Elec.	Ther.
Avg. Load (MW)	2.41	1.18	1.49	1.47	208	107
Peak Load (MW)	3.66	1.77	2.35	4.47	329	229
Load Factor	0.66	0.67	0.64	0.33	0.63	0.47
Peak Month	February	February	May	December	July	January
Day-to-Day Var.	3.96%	4.47%	13.16%	16.79%	7.47%	16.13%
Timestamp Var.	2.70%	3.65%	8.58%	9.19%	3.86%	6.72%

After reviewing several surveys of grid modeling tools (Lyden, Pepper, and Tuohy 2018; Ringkjøb, Haugan, and Solbrekke 2018; Sinha and Chandel 2014), I concluded that the HOMER (Hybrid Optimization of Multiple Energy Resources) software developed by the

National Renewable Energy Laboratory (NREL) was the most appropriate modeling tool for this work. HOMER takes hourly electric load data as an input, downloads renewable resource and temperature data from NASA databases, and optimizes the microgrid system for lowest cost over every possible combination of included energy resources to meet demand. I created four separate grid scenarios for HOMER to optimize: 100% diesel (the business-as-usual scenario), 100% nuclear, nuclear with diesel, and nuclear with batteries. All scenarios were run first without renewables and then with renewables. Lastly, I ran a 100% renewables and batteries scenario to offer a comparative carbon-free microgrid.

Since the two off-grid communities rely on diesel power for 100% of the electricity and heating needs, this first scenario serves as a baseline for comparison. I included each community's existing diesel generator capacity. I set the initial capital cost of the diesel generators to zero. Diesel generators are replaced regularly, and I varied the operating lifetime from 20,000-80,000 hours, with a replacement cost of $\$550/kW$. I varied the price of fuel from $\$0.5 - 3$ per liter, which is consistent with the cost of delivered fuel in this region over the last several years.

The HOMER software does not include nuclear energy in its suite of generation options. I created a custom generator to approximate a microreactor module in two different ways. Neither option is perfect but each can provide different insights and comparing the sensitivity of the results for each method proved valuable.

The first method involved creating a custom non-renewable power source (NPS), where the user specifies a fixed, continuous power output, along with capital cost, replacement cost, annual $O\&M$ cost, and other performance and maintenance factors. Details for these parameters are provided in Table 3. This essentially models a microreactor like a wind turbine with a continuous output of electricity; the "non-renewable" distinction only matters insofar as HOMER provides a share of renewables electricity as an output metric for every potential system it evaluates. The main downside of the NPS model is that it assumes the nuclear unit generates at 100% capacity year-round, with no load-following. Fuel cost are also fixed and must be included with annual operations and maintenance costs.

The second method to model a microreactor involved creating a custom generator, with an accompanying custom fuel source (uranium). In this case, the generator is modeled like a diesel generator, with a specified capacity but the ability to load-follow. For the custom fuel, the user must specify the fuel price along with the heating rate in units of kg/kWh. The benefit of the generator model is that each 1MW reactor is modeled separately and allowed to load-follow. In addition, the reactor lifetime is based on operating hours, not fixed years like for the NPS model. For both methods of modeling nuclear, I used fuel and $O\&M$ cost data from the median global figure for LWRs from the IEA's 2015 Projected Cost of Generating Electricity (International Energy Agency 2015), which also happened to be the U.S. figure. I included the full range of costs for global figures in the sensitivity analysis. A comparison of these two methods is provided in Appendix B.1.

For the baseline nuclear scenario, I let HOMER optimize a microgrid consisting solely of nuclear, choosing the optimum number of 1MWe reactors. For the Generator model, HOMER also determines how each reactor generates electricity every hour of the year, giving a unique load profile for each. After running a 100% nuclear optimization, I add in wind and solar technologies and re-run the optimization. Model parameters for the microgrid and all included technologies are provided in Table 3.

Finally, HOMER includes links to NASA data sets for global temperature, solar radiation, and wind speed. Using monthly averages specific to the microgrid location, HOMER synthesizes hourly temperature and renewable resource data over the whole year. A full detailing of the modeling parameters used in this HOMER model is provided in Appendix B.2.

3.3 Results

I modeled optimal mixes for each of the four technological scenarios for each case study: two Canadian communities, the Fairbanks hospital, and the University of Wisconsin campus. In what follows, I first report the results of modeling the optimal electricity system for the two Canadian communities, which are very similar in structure but differ in scale. The results for the optimal electric systems are broadly similar for the hospital and college campus case study; however, I also model their thermal demand and more details is provided for those systems.

3.3.1 Off-Grid Canadian Community Results

I provide detailed results for the larger Canadian off-grid community (Community A) and summarize results for the smaller community (Community B), which is very similar to Community A in demand profile. Detailed results for Community B are available in Appendix B.3. In 2015, average annual electric load in the Community A was 2.41MW, with a minimum load of 1.50MW in July and a maximum load of 3.66MW in February. Total electric consumption for 2015 was 21.14GWh, up 3.4% from 2014 and 7.0% from 2013.

For the baseline scenario in which all of Community A's electricity demand is provided with diesel generation, the total net present cost was \$85 million, for a 25-year project lifetime. This results in a levelized cost of electricity of \$0.31/kWh. Adding wind and solar options, the lowest cost system includes four 1.5MW wind turbines, resulting in a lower net present cost of \$81 million, with a LCOE of \$0.29/kWh.

100% Nuclear

Given that Community A's peak electric load in 2015 was 3.6MW, the HOMER optimization resulted in building four 1MWe reactors, at a net present cost of \$51 million and a levelized cost of energy of \$0.18/kWh. The annual load factor for the four reactors is 60%, but the resulting cost is still less than diesel alone. When renewables are added to the system, HOMER finds the lowest cost system still includes four 1MWe reactors but also a single 1.5MW wind turbine, for a slightly higher net present cost.

Nuclear and Diesel

When HOMER was allowed to optimize over both nuclear and diesel fuels, the lowest cost scenario covers all of the load with four 1MWe nuclear reactors. However, the optimal system also includes 4.1 MWe of diesel capacity, although it only operates for two hours during the year, on one evening in February - clearly not a scenario that anyone would adopt. The reason for this result appears to be a means of maintaining operating reserves on the fourth nuclear reactor. As diesel is much more expensive than the nuclear reactors, it is not surprising that the optimal system closely resembles the 100% nuclear scenario. The next best scenario, which includes significantly more diesel, only has three 1 MWe reactors, with a higher net present cost of \$52 million and a levelized cost of \$0.19/kWh. However, this system releases about 5,000 tonnes of CO2 over the course of the year.

When renewables are added to this portfolio, only three 1 MWe reactors are built, and one 1.5MW wind turbine is included. Yet the amount of electricity generated from diesel increases significantly, to about 8% of total electricity. This system is more expensive than

Table 3.2: Comparison of optimal system configuration for Community A's 2015 electric load under differing technological mixes.

	Lowest Cost	**Lowest Cost & Zero Carbon**
Including Nuclear	3MW Nuclear + 5.3MWH Battery, $LCOE = \$0.16/kWh$	3MW Nuclear + 5.3MWH Battery, $LCOE = \$0.16/kWh$
Excluding Nuclear	4.1MW Diesel + 6MW Wind, $LCOE = \$0.29/kWh$	54MW PV + 21MW Wind + 325MWh Battery, $LCOE = \$1.0/kWh$

either the 100% nuclear scenario or the nuclear with diesel scenario.

Nuclear and Batteries

When batteries were added to the portfolio, HOMER optimized the system to include only three 1 MWe nuclear reactors with a 5.3MWh lead-acid battery. That's approximately 8,600 car batteries. The net present cost of this system is much lower than the other alternative: $44 million with an LCOE of $\$0.16/kWh$. Including renewables reduces the cost slightly, although the amount of renewable energy generated is less than 10% of electricity generation.

100% Renewables

Lastly, I optimized over a renewables and batteries scenario. The result was a significant over build of capacity: 54MW solar PV, 21MW wind, and 325MWh of lead-acid batteries. The net present cost was more than double the next cheapest scenario, $285 million with a levelized cost of $1.0/kWh. This system generates 72% more electricity than demand over the year, an excess 60 GWh. If the excess generation could be harnessed to make synthetic fuels for heating and transport, that might make the system more attractive.

Table 3.3: Comparison of optimal system configuration for Community B's 2015 electric load under differing technological mixes.

	Lowest Cost	**Lowest Cost & Zero Carbon**
Including Nuclear	2MW Nuclear, $LCOE = \$0.20/kWh$	2MW Nuclear, $LCOE = \$0.20/kWh$
Excluding Nuclear	2MW Diesel + 4.5MW Wind, $LCOE = \$0.28/kWh$	5.2MW PV + 13.5MW Wind + 87MWh Battery, $LCOE = \$0.81/kWh$

Community B Results

In 2015, average annual electric load in Community B was 1.18MW, with a minimum load of 0.68MW in June and a maximum load of 1.77MW in February. Total electric consumption for 2015 was 10.3GWh, up 6% from 2014 and 12% from 2013. For the baseline scenario, covering all of Community B's electricity demand with diesel generation, the total net present cost was $\$46 million$, for a 25-year project lifetime. This results in a levelized cost of electricity of $\$0.34/kWh$. Adding wind and solar options, the lowest cost system includes three 1.5MW wind turbines, resulting in a lower net present cost of \$37 million, with a LCOE of $\$0.28/kWh$. A full description of the results for Community B is provided in Appendix B.3; in Table 5 below I provide the optimal system mix for each scenario.

The results are broadly similar to the Community A case study. The nuclear and batteries scenario is the cheapest overall system, but unlike for the larger community adding renewables raises the overall cost. Although I don't have thermal load data for either of these two communities, from interviews I know that they do not have a centralized heating system and that most residential and commercial heating is electric. Therefore, the electric load data that I have should cover most of the non-transportation energy demand of these communities.

3.3.2 Case Studies Including Thermal Demand

The large hospital in Fairbanks has a similar peak electric load to the smaller of the two off-grid Canadian communities but also includes thermal demand data. Therefore, I expanded the model in HOMER to include a combined heat and power system. The hospital has an average electric load of 1.49MW, a minimum load of 0.68MW that occurs in the early morning in mid-January, and a maximum load of 2.35MW that occurs in late March. The load factor for the system is 64%. As the hospital is connected to the grid, I did not use a 100% diesel system as the baseline, but compared costs with utility electricity rates in Fairbanks. The lowest cost mix was actually 100% nuclear, where HOMER optimizes the system to have three 1 MWe microreactors with a total NPC of $\$37M$ and an LCOE of $\$0.22/kWh$. This is actually cost-competitive with retail electricity prices in Fairbanks: $\$0.24/kWh$ for residential customers and $\$0.22/kWh$ for commercial customers (Golden Valley Electric Association 2020).

Looking at the thermal demand next, the Fairbanks hospital has an average load of 1.47MW, very similar to the average electric load. The peak thermal load is 4.47MW and occurs in December. Adding a stand-alone boiler to meet this thermal load costs $\$0.04 - 0.12/kWh$ depending on if the boiler is fueled by natural gas or diesel. I am also able to include a Combined Heat and Power (CHP) system, where the boiler uses excess heat from the microreactor. Allowing for 85% of the waste heat from the microreactors to go towards the boiler reduces the price for heat to 1.8 cents/kWh for diesel and 0.6 cents/kWh for natural gas, while also saving over 1 million liters of diesel or 1 million cubic meters of natural gas every year.

For the University of Wisconsin Madison case, the average electric load was too large to rely on 1MWe microreactors. Instead I used a generic 50MWe reactor —approximating a NuScale SMR module with a capital cost of $\$4,500/kW$ and a lifetime of 40 years. The optimal system included six 50MW reactors and 160MW of lead-acid batteries at a total cost of $\$2.3B$ and an LCOE of $\$0.10/kWh$. To be cost-competitive with the wholesale electricity rate from the local grid (roughly $\$0.03/kWh$), UW would need a CO2 price of $\$120/tonne$. If I use a discount rate of 3% instead of the HOMER default of 8%, the LCOE falls to $\$0.066/kWh$ and the necessary carbon price would be $\$60/tonne$ to be cost-competitive with wholesale prices in Madison.

Looking at thermal demand, the total thermal demand over the course of a year for UW is about half of the electricity demand, with an average load of 110MW and a peak load of 230MW, which occurs in January. Adding a stand-alone boiler to meet this thermal load costs $\$0.025/kWh$, assuming natural gas fuel. Allowing for 85% of the waste heat from the nuclear system to be used for thermal demand covers 100% of the thermal load over the year, meaning the price for heat is $\$0.0/kWh$. This saves over 112 million cubic feet of natural gas annually and $300 million over the 25-year project evaluation period.

3.3.3 Sensitivity Analysis

Whether micronuclear could be cost-competitive with diesel generation depends on a variety of parameters for both technologies. The levelized cost of electricity from diesel is most sensitive to the cost of diesel fuel, which varies by method of transport and time of year. In this region of Canada, diesel has been around $\$1/L$ for off-grid communities over the last few years (Lovekin and Heerema 2019), and that is what I used in the baseline scenarios. Varying the cost of diesel plus or minus 50% changes the LCOE +39% and −47% respectively. A change in generator lifetime or $O\&M$ costs by ±50% changes the LCOE of diesel by only a few percent. A tornado plot of the sensitivity results is provided in Figure 3-1.

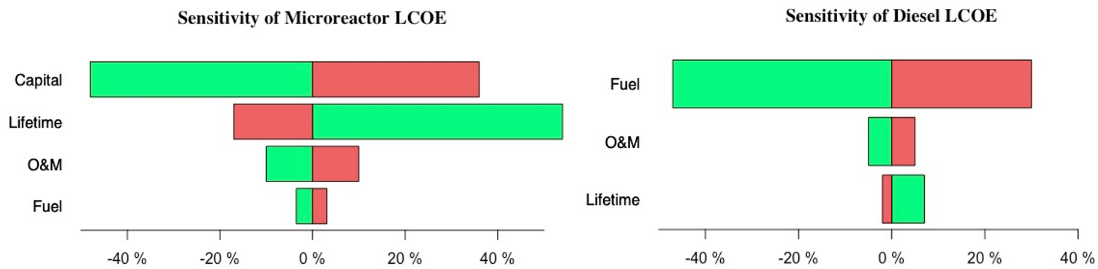

Figure 3-1: Sensitivity of levelized cost of electricity for nuclear (left) and diesel (right). For all parameters, the input was varied by $\pm 50\%$. For nuclear, the baseline parameters were $\$10,000/kW$ for capital cost, 10 years for lifetime, $\$790,000/yr$ for $O\&M$, and $\$550/kg$ for fuel. For diesel generation the baseline parameters were $\$1/liter$ for fuel, 40,000 hours for lifetime, and $\$0.02/kWh$ for $O\&M$.

For micronuclear, the LCOE is most sensitive to the capital cost. Although reactor lifetime could also be a significant driver of costs at shorter lifetimes. I used $\$10,000/kW$ as our baseline capital cost, but changing the cost by $\pm 50\%$ changed the LCOE by $+36\%$ and -48% respectively. Figure 3-2 shows LCOE as a function of reactor lifetime and initial capital cost. As reactor lifetime increases from 5 to 10 years, LCOE decreases by 54% for the baseline scenario, whereas increasing the reactor lifetime from 10 to 15 years reduces the LCOE by only 20%. Changing the $O\&M$ costs and fuel costs by $\pm 50\%$ change the LCOE by only a few percent.

From Figure 3-2, I conclude that at current diesel prices of $\$1/L$, a microreactor needs to be less than $\$15,000/kW$ and have a lifetime greater than 10 years to be cost-competitive. If diesel becomes more expensive, rising to $\$2/L$ then the microreactor is cost-competitive up to an initial cost of $\$25,000/kW$ as long as the reactor lifetime is greater than 10 years.

The results of the modeling are also quite sensitive to the discount rate applied. Not only does this change the levelized cost of electricity but also the optimal mix of generators deployed. For example, for the University of Wisconsin Madison case study, for discount

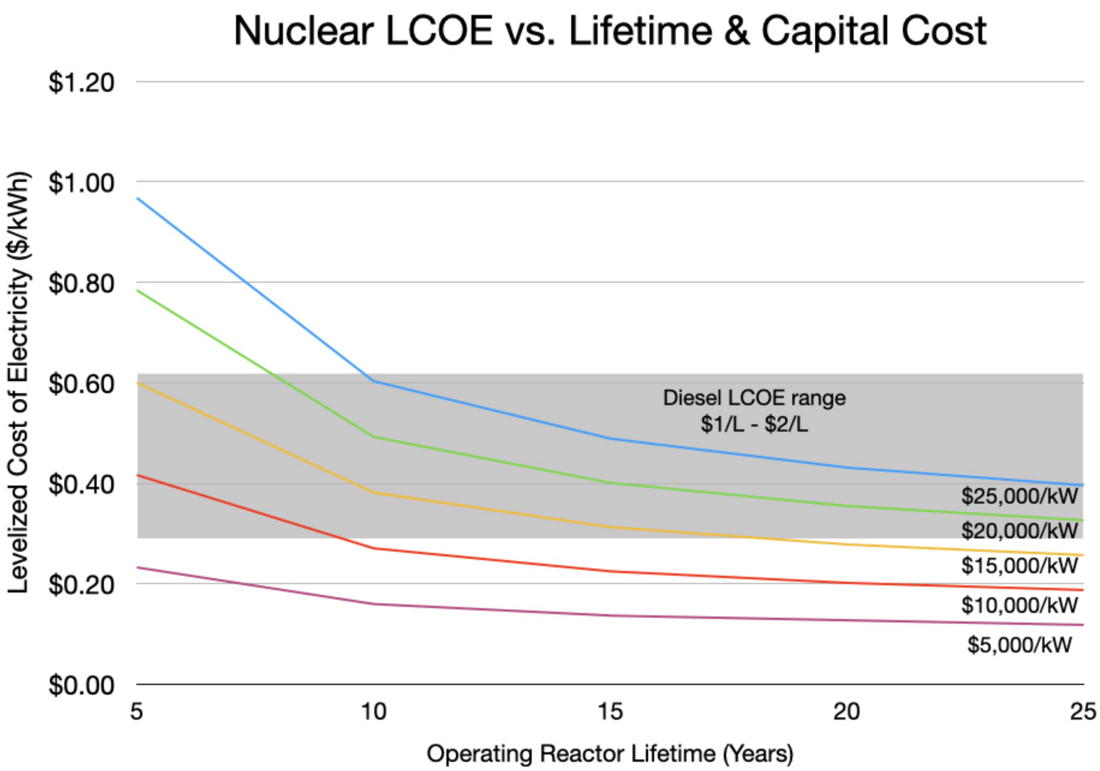

Figure 3-2: Levelized cost of electricity for a 100% nuclear system, shown as a function of reactor lifetime and initial capital cost. The range of LCOE for the same system with 100% diesel generation is shown over a range of diesel prices from $\$1/L - \$2/L$. This analysis used the Generator model for the microreactor.

rates below 6%, the optimal system is 100% nuclear (seven 50MW reactors), whereas for discount rates above 6% the optimal system is six 50MW reactors and 164MW of lead-acid batteries. This makes sense: higher discount rates favor systems with lower capital costs but higher $O\&M$ costs, whereas lower discount rates favor higher capital costs and lower $O\&M$ costs. This has implications for understanding the optimal system under different ownership models of microgrids and the nuclear reactors.

3.4 Discussion

Across the renewable microgrid literature, it is common to find diesel generators as the backbone that supports increasing penetrations of renewable energy. With the declining cost of batteries, systems that rely solely on renewables are becoming increasingly feasible, especially for communities with low energy needs and high renewable resource potential. However, our modeling shows that nuclear could be another option for both offsetting diesel capacity and generation, but also serving as the balancing capacity for renewable-heavy systems.

To expand on these potential trade-offs, I compare the optimal microgrid portfolios for Community A in 2015 under different technological constraints: business as usual; least-cost mix excluding nuclear; least-cost mix excluding nuclear and diesel. The overall optimal mix – nuclear with batteries – saves \$48 million and avoids 350kt CO2 emissions over the 25-year project lifetime. Compared with this optimal mix, excluding nuclear increases the total net present cost by \$39 million and increases CO2 emissions by 240kt. The 100% renewables scenario saves 350kt CO2 compared with the business-as-usual scenario, but adds \$237 million to the total cost, implying a carbon price of \$670/*tonne*.

Early deployment of microreactors will likely target off-grid applications where potential customers are currently paying high prices for electricity and heating. Penalties for air pollution of payments for reliability could help make microreactors more competitive against diesel in some areas, but it is apparent that they could already be competitive in certain niche markets without including externalities.

For microreactors to be competitive with diesel on microgrids outside of these high-diesel price niche markets, the cost of nuclear will need to come down considerably. For the University of Wisconsin example, there needs to be a carbon price of $\$120/tonne$ for nuclear to be cost-competitive with natural gas. Reducing the nuclear $O\&M$ costs by 15% reduces the LCOE by half a cent, and every reduction of the capital costs by $\$1,000/kW$ reduces the LCOE by 1 cent. With $O\&M$ reduced by 30% and capital costs reduced to $\$2,500$, the LCOE of electricity for UW is $\$0.067/kWh$. This would still require a carbon price of $\$65/tonne$ to be cost-competitive with the wholesale price of electricity in Madison. This implies that stand-alone microreactors would only be feasible in areas with very high electricity prices or with high carbon prices or both.

However, demonstrating microreactors in these niche markets could not only prove the concept, but also start driving capital costs down as the first dozen units get built in a centralized facility. For this analysis, I used $O\&M$ costs taken from traditional large-scale light-water nuclear reactors. Yet many microreactors developers are aiming for streamlined designs with increased automation and remote monitoring. These capabilities could reduce $O\&M$ significantly, but that will remain uncertain until first demonstrations.

The load-following capabilities of microreactors could also be a concern. Large light-water reactors typically do not load-follow due to economic reasons (high capital cost and low variable costs), and this will likely be the case for microreactors as well. However, if microreactors comprise a large share of the generation capacity on a microgrid, they will be required to load-follow to a larger extent. The Electric Power Research Institute's (EPRI) User Requirements Document lays out operational targets for potential SMRs. They suggest that SMRs should be capable of ramping up or down at a rate of 40% of capacity per hour and a step change of 20% in ten minutes. For a 1MWe microreactors that would translate to a minimum ramp rate of 400kW per hour and 200kW in ten minutes. To check if these conditions would be violated in a 100% nuclear-powered microgrid, I looked at the hourly variability of the electric load across the case studies and found that they never exceeded these ramping constraints. This also highlights the resiliency value of having multiple smaller reactors, rather than one large reactors, as the load-following could be spread across different units.

Lastly, this analysis has only looked at how microreactors could meet existing energy demands for each case. There is also the possibility that access to large-scale, reliable electricity could spur demand, especially for the remote communities. For example, large-scale livestock operations or indoor vegetable operations would require significant heating a lighting capability in northern Canada. These are both industries that such communities have expressed an interest in pursuing. Another potential industry is hosting commercial data centers.

3.5 Conclusion

The existing microgrid literature reflects a dynamic global market with ongoing technological developments and cost reductions. For communities around the world that are not yet electrified, developing a microgrid could be cheaper than extending the central grid. With declining costs of renewables and batteries, these systems could power even larger communities closer to the existing grid. In the developed world, microgrids are gaining popularity within existing power grids as a way to enhance resiliency, reliability, and local ownership. Up until now, nuclear power has been too large to fit into these conversations, even SMRs of 100-300MW may be too large.

Yet with the development of commercial microreactors, there is a need to understand not only the economics of how they could be deployed on microgrids, but also how microreactors might interact with other energy sources and how a hybrid system could meet demand over the year. Our analysis shows that microreactors could be cost-competitive with diesel generators for certain applications where diesel costs are high or reliability is mission-critical. However, no form of new nuclear is presently cost-competitive with grid electricity in the U.S., especially where powered by natural gas. For nuclear to be cost-competitive for on-grid microgrids, both the capital and $O\&M$ costs will need to be reduced, and there will need to be access to low-cost financing. Even then, microreactors may not be cost-competitive without a carbon price or reliability payment.

Governments could have several motivations to support microreactor deployment, from improving public health and environmental outcomes by reducing air pollution from diesel, or reducing energy costs and increasing reliability for communities. Policies that could bring down the costs of microreactors include demand incentives like federal Power Purchase Agreements, procurement mandates, production and investment tax credits. To reduce the investment costs, governments could offer loan guarantees and direct financing such as were done through the U.S. Rural Electrification Administration.

Chapter 4

Trade-offs between economies of scale and economies of volume for very small modular nuclear reactors

Abstract

To understand the trade-offs between economies of scale and factory fabrication of future SMRs, I perform a series of analyses that establish boundaries on the cost trajectories of different sized reactors. First, I use a multi-factor regression to determine the scaling factors and learning rates of historical nuclear reactor fleets. These estimates are combined with those from other energy technologies to establish a feasible range for future factory-fabricated nuclear reactors. Second, I find an analytical solution to the break-even point where the SMR unit cost becomes cheaper than a large nuclear reactor, assuming the SMR starts more expensive but experience faster learning. Finally, I take the range of feasible scaling factors and learning rates to calculate how many SMRs - of different sizes- would need to be built to reach cost-parity with a modern large nuclear reactor.

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Lovering, J.R. and J.R. McBride. "Chasing Cheap Nuclear: Economic Trade-Offs for Small Modular Reactors." *The Bridge* National Academy of Engineering. Fall (2020).

4.1 Introduction

Demand for clean energy is growing rapidly as more countries commit to deep decarbonization, but there is also a need for sources of firm low-carbon power to ease the transition (Sepulveda et al. 2018). Whether nuclear power plays a prominent role in this energy transition will depend in large part on costs. For this reason, many developers have focused on novel nuclear designs that have the potential to be cheaper and faster to build, particularly shifting the paradigm of nuclear power away from large-scale construction projects and towards smaller, factory-fabricated modular products, i.e Small Modular Reactors (SMRs). Yet it remains unclear whether SMRs will be cost-competitive with the fossil fuels they are aiming to replace.

Estimating the future cost of an emerging technology is always difficult, but this is especially true of nuclear technologies that have historically been plagued with over-optimistic cost estimates and large cost-overruns (Koomey and Hultman 2007; Sovacool, Gilbert, and Nugent 2014). First-of-a-kind (FOAK) unit costs are expected to be high when compared with current large light-water reactors (LWRs), with the expectation that costs will come down as more units are fabricated. There is a debate in the nuclear industry about whether diseconomies of scale will triumph over economies of volume, implying that small and very small reactors — so-called microreactors less than 10MWe — will be unable to reach cost-parity with large reactor designs (Froese, Kunz, and Ramana 2020). However, recent projects to build large reactors in the U.S. and Europe have proven to be prohibitively expensive and costs have escalated over time. A variety of utilities in the Americas, Europe, and Asia are considering building SMRs as an alternative to new investment in large reactors. More importantly, if costs can be reduced, SMRs and especially microreactors may be able to open up new markets for nuclear for municipal utilities, industrial customers, and off-grid and microgrids systems. If small reactors can achieve consistent and significant levels of positive learning over sustained deployment, the prospect of reaching unit-cost parity with large designs becomes feasible.

In many ways, the future of SMRs might parallel solar photovoltaic technology as it stood in the 1970s. Early solar PV panels had similarly high unit costs, starting at $\$100,000/kW$, but coming down below $\$2,000/kW$ in the last decade (Nemet 2006). First applications targeted niche markets like spacecraft and remote installations. And while solar panels may seem like a simpler technology — and can therefore experience faster learning — a modern jet engine turbine rivals a nuclear reactor in its complexity, with peak power in the 10s of MW. Yet today, through economies of volume, jet engines can cost less than $\$1,000/kW$.[1] Assuming that modular nuclear designs can manage to clear the gauntlet of regulatory issues and public acceptance, the answer to whether they can then follow a similar cost evolution to solar panels or jet turbines will depend on two key factors: 1) economies of scale, and 2) economies of volume.

4.1.1 Economies of Scale for Nuclear Energy

Predictions for the rapid growth of commercial nuclear power in the 1950s were predicated on the expectation that the larger and more mature reactors of the future would be more cost-efficient. But such economies of scale were not fully realized. Early commercial reactors in the U.S. had capacities of approximately 250 – 500 MWe per reactor. Beginning in the 1960s, the industry began building larger reactors, approaching 1 GWe per reactor. When constructed, these later, larger reactors were considerably more expensive per kW than

[1] Example: A GE 90-115B engine used on a Boeing 777 aircraft has a peak output of 23MW (Duivis 2018). One estimate from KLM put the cost of this engine at \$12-\$35 million (van Damme and Stolk-Oele 2017), which is equivalent to \$520/kW-\$1,500/kW.

the earlier, smaller reactors. This contradicted the expectation of economies of scale and contributed to the sharp decline in nuclear construction in the US.

Scaling relations are frequently used in engineering and industrial economics to predict the cost of scaled-up or scaled-down versions of equipment and processes (although it is much more common to use them for scaling up). For commercial nuclear reactors, scaling relations can connect the empirical costs of large reactors with expected costs of smaller reactors. In a 2013 report, *Approaches for Assessing the Economic Competitiveness of Small and Medium Sized Reactors*, the IAEA attempted to quantify the trade-offs between economies of scale and other economies for Small Modular Reactors (IAEA 2013). They propose a scaling relation to predict the FOAK cost for an SMR module, given by Equation 4.1.

$$Cost_{SMR} = Cost_{NPP} \times \left(\frac{SMR\, MW_e}{NPP\, MW_e}\right)^{n-1} \tag{4.1}$$

where $Cost_{SMR}$ is the overnight capital cost of the SMR per unit of capacity, $Cost_{NPP}$ is the overnight capital cost of a large-scale nuclear power plant (NPP) per unit of capacity, MW_e is the rated power capacity of each, and n is the scaling factor. I apply the IAEA scaling relation, Equation 4.1, to the cost and size of a Westinghouse AP1000 reactor being built in the U.S., assuming an $OCC = \$5,500/kW$ and $Capacity = 1,100MW$. Figure 4-1 shows the hypothetical First-of-a-Kind costs for an SMR as a function of capacity, from 2.5MW to 300MW. I show four scaling curves covering the full range of scaling factors considered by IAEA, $n = 0.4 - 0.7$.

Froese et al. (2020) and Moore (2016) use this scaling relation to estimate the costs of microreactors and conclude that the cost would be too high to be feasible. However, there is ongoing debate about how applicable such scaling relations are to SMRs and especially to

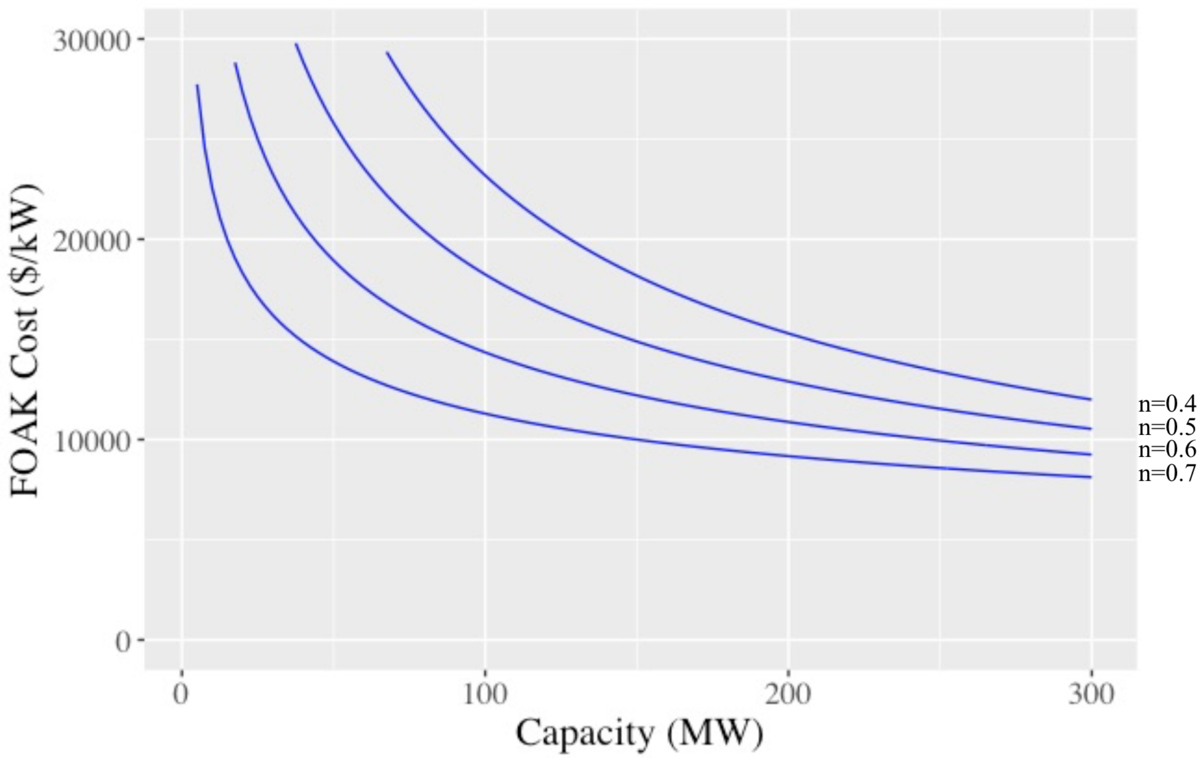

Figure 4-1: Illustration of the IAEA scaling relation for a base plant of $OCC = \$5,500/kW$ and $Capacity = 1100MW$. The blue lines show the first-of-a-kind cost for an SMR as a function of size in MW for four different scaling factors. Note that for reactors less than 10MW, microreactors, the cost becomes quite large.

microreactors. If an SMR design is very similar to a large LWR, simply a scaled-down version, then such relations are probably appropriate. Yet for nuclear power, historical experience has shown that economies of scale achieve diminishing returns as reactors get very large. Perhaps the opposite is true as well: microreactors could be too dissimilar, especially when radically simpler engineering is involved, such that economies of scale cease to apply. Yet even if small and microreactors start out 10x-20x as expensive, perhaps they will benefit from faster learning rates.

4.1.2 Learning-by-doing for Nuclear Energy

As microreactors are deployed in a standardized series, we can expect unit costs to fall over cumulative deployment in a process known as economies of volume or learning-by-doing. The concept of technological learning was first calculated for aircraft production in the 1930s (see for example Argote and Epple (1990)). For large power plants constructed individually and on site, the more common metric is to look at how capital costs decline with cumulative installed capacity. These so-called "experience curves" track industry-wide learning across a country or region, rather than on an assembly line. Early studies of cost trends for nuclear power found that the technology had experienced positive learning (Cantor and Hewlett 1988), meaning construction costs decreased with increased firm experience. More recent analysis has found negative learning however, where costs increase as firms or countries gain experience (Grubler 2010; Cooper 2010).

Using the standard learning curve formulation, the cost of the u^{th} unit built for each reactor is given by Equations 4.2, where $c_{1,0}$ is the first-of-a-kind cost for each reactor and b_1 and b_2 are the learning factors for each reactor.

$$c(u) = c_0 u^b \tag{4.2}$$

Since commercial nuclear power reactors have never been deployed as factory-produced products, there is little understanding of how the cost of reactors would evolve if they were constructed using standardized, sequential factory production. Therefore, estimating potential learning effects is a theoretical exercise. By combining analysis of scaling and learning-by-doing, this chapter explores the theoretical deployment levels where microreactors reach unit-cost parity with conventional reactors as a function of starting costs, learning rates, and scaling factors. Using the ranges of possible values for each parameter, I illustrate potential pathways for microreactor cost evolution. This study serves two purposes: first, it establishes realistic boundaries on the cost evolution for SMRs and microreactors to help inform investment policy; second, it provides empirical support for attempts to understand comparative learning and scaling effects in factory-fabricated nuclear reactors. I conclude by recommending policies that could drive learning effects and minimize diseconomies of scale.

4.1.3 Literature Review

There are two major bodies of work across the literature on nuclear economics: studies that analyze what drove costs historically, and studies that project what will influence costs in the future. How much future cost drivers are related to historic cost drives will depend on how similar both the regulatory and legal environments and the technologies and construction processes are. Focusing on the latter, for Small Modular Reactors, the most relevant factors from these studies are economies of scale and economies of volume (or learning-by-doing). Even on these topics, there is significant disagreement as to the size of such effects, and whether these models are even applicable to nuclear technologies.

Beginning in the 1970s, several studies used multi-factor regressions to analyze the correlates of U.S. nuclear costs and leadtimes. W. E. Mooz (1978) and W. Mooz (1979) found significant experiential learning at the level of the Architect-Engineering (A-E) firm of about 10%, i.e. costs decreased by 10% for every doubling of reactors built by a given A-E firm. Mooz also looked at industry-wide learning and the result was not significant, nor were there scaling effects. Paik and Schriver (1980) performed a similar analysis to that of Mooz (1979) but with a different measure of regulatory effects. They also found no significant scaling effect, but found learning rates of 28% for the A-E firms.

Komanoff (1981) performed a similar series of regressions, but also ran a regression that included two levels of learning: one coefficient for A-E experience and one coefficient for industry wide experience. They found a positive learning rate of 7% for A-E experience, but a negative 21% learning rate for industry experience. Zimmerman (1982) found similar results to those of previous studies, with A-E firm learning at 12% and no significant scaling effect. Zimmerman also performed a multi-factor regression analysis to examine the difference between projected and realized costs, and found that an overestimation of scaling effects was one significant contributor to cost overruns; the more important factor was delays.

Cantor and Hewlett (1988)) critiqued these previous regressions while also developing their own model: a two stage least squares regression with an instrumental variable. Their second regression equation estimated lead time given a set of independent variables. Then the first equation was used recursively to determine cost based on the estimated lead time and other variables. Demand for the plant was used as the instrumental variable – something that potentially affects lead time but not cost. Notably, they did not consider industry-wide learning as the variable is highly correlated with time. The only factors that significantly reduced costs were increased unit size and whether the utility was the construction manager.

Bowers, Fuller, and Myers (1983) surveyed studies of economies of scale in nuclear power and collected scaling factors from 26 studies. They found a range from $n = 0.25$ to $n = 1$ (the latter indicating no scaling effect). Unfortunately, these studies only include nuclear cost data through 1982, and are largely constrained to the U.S. Despite these limitations, the scaling factors from Bowers et al. (1987) are still widely used. For example, Carelli et al. (2010) used these scaling factors to model potential costs for small and medium modular reactors and found that higher costs for smaller reactors from economies of scale could potentially be offset by modularization and fabrication strategies. In a more recent study, the IAEA used the median value of $n = 0.6$ from Bowers for their 250MW SMR case study (IAEA

2013). Moore (2016) uses the midpoint value, $n = 0.55$, from Bowers range of scaling factors when he scales down the cost of a 1,000MW reactor to a 10MW microreactor. Froese, Kunz, and Ramana (2020) used the same scaling relation, but with a higher cost for the LWR cost, to estimate that a 3MW microreactor would cost $130,000/kW with a levelized cost of electricity almost ten times that of wind or diesel.

Beginning in the late 1970s and early 1980s, there is a growing literature comparing nuclear cost experiences across countries. **Marshall1981** argued that performing regressions on overnight cost for nuclear power plants rather than total costs biases coefficient for scaling and regulatory effects because relying on overnight costs tends to overestimate the impact from economies of scale and underestimate the impact from regulatory changes. Applying a standard regression model as detailed in the studies above, they look at both overnight and true cost data for 34 LWRs in Japan. As expected, they found a significant effect from economies of scale when regressing on overnight cost, but no significant effect when looking at true costs. MacKerron (1992) surveyed trends in nuclear costs across six countries: the US, UK, Canada and Germany, France and South Korea. He concluded that economies of scale were not realized, likely due to increasing complexity of designs and difficulty in managing safety. Like previous studies, MacKerron argued that the large size of reactors was not inherently the problem, but a lack of design standardization and rapid growth in reactor capacities. Vendors and contractors were not able to learn from previous builds and implement innovations in materials and construction processes that might have reduced costs.

Berthélemy and Escobar-Rangel (2015) applied the two-stage regression model from Cantor and Hewlett (1988) but looked at a larger data set of costs for 128 reactors in the U.S. and France. They found significant learning effects, but only within Architect-Engineer firms. Their results show the importance of reactor standardization, by reducing leadtimes, one of the largest drivers of overnight cost. A different study from the same group, Escobar-Rangel and Lévêque (2015) looked more closely at the French data and performed a linear regression on levelized cost of electricity from individual reactors. They found that there was significant learning and absolute cost reductions within each reactor "pallier" or class, but that when the industry introduced a new (and larger) reactor class, costs jumped and performance declined.

Starting in the 1990s, there has been a shift toward calculating industry-wide or country-wide learning rates for energy technologies, where costs are regressed against total capacity installed. The reason is that it is much easier to project in energy systems modeling, particularly for use in decarbonization scenarios where cost can be simply modeled as a function of cumulative deployed capacity. McDonald and Schrattenholzer (2001) aggregated 26 data sets of energy technology learning curves. They only found one study that looks at nuclear power, which found a learning rate of 5.8% for reactors built from 1975-1993 across the OECD. Later studies that look at industry-wide learning include Sturm (1994), Grubler (2010), and Cooper (2010). Sturm (1994) looked at learning in nuclear power plant operations and found positive learning in OECD countries but negative learning in Eastern European countries. They suggested that there may have been disruptions to learning due to the collapse of the Soviet Union. Grubler (2010) and Cooper (2010) both look at U.S. data and newly released French data to come to the same conclusion, namely that both countries experienced negative learning (i.e. reactors got more expensive as countries gained experience). Nuclear power is not alone among energy technologies in experiencing negative learning rates. Rubin et al. (2015) found that onshore wind and natural gas combined cycle plants also experienced negative learning during some time periods.

In recent years, there has also been a growing critique of the use of learning rates for power plants, and particularly the aggregation of learning rates for energy modeling.

Söderholm and Sundqvist (2007) critique the aggregation of learning rates across energy technologies and their inclusion in bottom-up energy models. For example, they note that many studies present a range of learning rates for a single technology and assume that is a variation within the technology, rather than a result of different methods for estimating the learning rate. Often several studies will use the exact same data, but reach very different estimates of learning rates based on how they formulate their model. More importantly, Söderholm and Sundqvist have noted that there is little reflection on the causal drivers in these relations, where most studies assume that there is a direct causal relation between cumulative capacity deployed and cost through a learning-by-doing effect, but there could likely be several omitted variables that are affecting both deployment and cost. To give just one example, if a technology gets cheaper, likely more will be deployed, but not if there is a physical or political constraint on future deployment. The authors hypothesized that effects like research, demand-side policies, or macroeconomic effects could be affecting both cost and deployment, but are not seriously investigated in most studies.

Performing a similar theoretical evaluation, Nordhaus (2009) found an upward bias in learning rate estimates when models do not include exogenous factors such as spillovers from other industries, research and development, and economies of scale and scope. Nordhaus argued that the use of learning curves persists in energy and climate modeling because it is one of the only theories of technological change that is simple to specify in a model: as you build more costs go down at a constant rate. An upward bias in learning rate leads to an underestimate in marginal costs for emissions mitigation and a preference for selecting technologies with higher expected learning rates.

Since no country has yet constructed a series of commercial SMRs, it is difficult to predict what the learning curve will be through the use of factory fabrication. However, learning rates of other electricity generating technologies provide useful context. Rubin et al. (2015) aggregated learning rates from the existing literature and found rates ranging from −11% for onshore wind and combined cycle natural gas to 47% for PV solar panels. Relevant to SMRs, two recent studies found that smaller energy technologies experience higher learning rates. Sweerts, Detz, and Zwaan (2020) collects learning rate estimates for 41 energy technologies across three categories: supply, demand, and storage. They find a 1.5% decrease in learning rate for each order of magnitude increase in size. The median learning rate for energy supply technologies was 12%. In a similar study, Wilson et al. (2020) looked at 32 studies of learning rates and found that for every order of magnitude increase in unit size the learning rate decreased by roughly 5 percentage points. This means that a 10kW unit had learning rates of 20%, while a 1MW unit had a learning rate of only 10%, with rates going negative around 100MW.

4.2 Methods and Data

As outlined below, there are two major parts to this analysis: 1) the use of multi-factor regression of historical cost data to asses broad ranges of scaling factors and learning rates, 2) calculation of the theoretical cross-over point where economies of volume outweigh economies of scale.

While there are serious limitations on the accuracy of learning rates and scaling factors that have been estimated from multi-factor regressions, such analyses can help put bounds on these effects for future nuclear technologies. Here I employ a more comprehensive global data set of nuclear construction costs across eight countries previously published in Lovering, Yip, and Nordhaus (2016). I decided to analyse scaling and learning factors at the country level for two reasons. For most countries, there is only one nuclear vendor that has supplied most of the country's nuclear power plants, often state-supported and in close partnership with a state-owned utility. For countries such as the U.S. and Japan where this is not the case, breaking down the nuclear fleet by vendor would result in too few reactors for a proper regression analysis. Therefore, the country-level analysis provides an estimation of learning and scaling effects across a country's nuclear industry. However, for the scaling factor, it is more important to narrow down the reactor technologies to a broadly similar set. For this reason, I exclude some demonstration and experimental reactors, or imported reactors that involve very different technology than that of the domestic fleet. This was particularly the case for the U.S. and France, which have two distinct eras of reactors that were disaggregated for this analysis. For the U.S., there is an early fleet of demonstration reactors and then a later, larger fleet of commercial LWRs. For France, there is an early fleet of six gas-cooled reactors and then their much larger fleet of PWRs. I exclude the early french reactor fleet from the regression analysis because six data points is too few to perform a meaningful analysis. Details on the reactors included and excluded for each country are provided in Table 4.1.

To estimate the empirical scaling factors and learning rates in these groups, I construct a multiple linear regression with ordinary least squares, shown in Equation 4.3. The regression specification is based on a simplified version of models employed by Cantor and Hewlett (1988) and Escobar-Rangel and Lévêque (2015), among others. The reason I did not use a more complex model specification is that I was not as concerned about predictive capabilities or accuracy, but was interested in cross-country comparison and relative effect sizes. Therefore, the model is limited to country-level experience (measured as cumulative capacity built), leadtime (months from construction start to grid connection), reactor capacity (in MW), and the number of reactors onsite. The latter being an alternative measure of economies of scale.

Table 4.1: A summary of the reactor cost data analyzed, from Lovering, Yip, and Nordhaus (2016). The reactors considered in each country were a subset of reactors of comparable technology. Hence, early demonstration reactors under 30MW were excluded. The largest reactor fleets in the U.S. and France were split into early demonstrations and later commercial eras.

Fleet	**Specified Reactor Type**	**Number**	**Capacity Range (MW)**
Canada	PHWR CANDUs	23	203 – 881
France1	GCRs, 1957-66	6	68 – 540
France2	PWRs, 1962-1991	59	280 – 1455
United Kingdom	GCRs, 1957-1963	22	138 – 625
India	All PHWRs	18	202 – 502
Japan	All LWRs	57	320 – 1325
South Korea	All PWRs	22	558 – 1340
	(excludes Canadian PHWRs)		
USA1	Demos, 1954-1963	17	3 – 265
USA2	Commercial LWRs, 1964-1978	113	436 – 1304
West Germany	LWRs	23	237 – 1307

$$log(OCC_i) = \beta_0 + \beta_{size} log(Capacity_i) + \beta_{leadtime} log(Leadtime_i) + \beta_{exp} log(CountryExp_i) + \beta_{AtSite}(AtSite_i) + \epsilon_i \tag{4.3}$$

Where I define the following variables:

OCC_i : Overnight construction cost in 2010 USD per kw

$Capacity_i$: Reactor capacity in MWe

$Leadtime_i$: Time between construction start and commercial operation

$CountryExp_i$: Cumulative installed capacity in MW constructed in country prior to reactor construction start

$AtSite_i$: Number of operating reactors at site at construction completion

It can be useful to present these regression coefficients as the more intuitive metrics of scaling factor and learning rate. To convert from the regression coefficient β_{size} to the scaling factor n, I use $n = \beta_{size} + 1$. To convert from the regression coefficient for country experience βexp to a learning rate, I use the following two equations: $b = e^{\beta exp}$ and $LR = 1 - 2^b$.

4.2.1 Calculating Break-Even Volumes

Once I have a range of scaling factors and learning rates from the historical cost data, I would like to understand the interplay between these two effects. The basic question is taking advantage of economies of scale, how many SMRs must be built to reach cost-parity with a large LWR.

To find this hypothetical cross-over point, I will assume two different nuclear reactor technologies. $Reactor_1$ is a conventional, large light-water reactor (hereafter referred to as "NPP"), while $Reactor_2$ is an SMR. Using the standard learning curve formulation, the cost of the u^{th} unit built for each reactor is given by Equations 4.4 and 4.5, where $c_{1,0}$ and $c_{2,0}$ is the first-of-a-kind cost for each reactor and b_1 and b_2 are the learning factors for each reactor. The learning rate can be found by: $LR = 1 - 2^b$.

$$c_1(u_1) = c_{1,0} u_1^{b_1} \tag{4.4}$$

$$c_2(u_2) = c_{2,0} u_2^{b_2} \tag{4.5}$$

From the theory of economies of scale, I expect FOAK SMRs to start out more expensive on a per unit basis, but they could become cost-competitive if they experience a faster learning rate. To test this, I calculate the break-even deployment needed to reach cost-parity between the two reactors. To find this point, I set c_1 and c_2 equal and solve for the number of units deployed. I begin with a simplistic – but perhaps generous – approach by assuming that the NPP experiences no learning, i.e. costs stay the same over successive unit builds, $c_1(u_1) = c_{1,0}$. Setting c_1 and c_2 equal and solving for u_2:

$$\begin{aligned} c_{1,0} &= c_{2,0} u_2^{b_2} \\ u_2^{b_2} &= \frac{c_{1,0}}{c_{2,0}} \\ u_2 &= \left(\frac{c_{1,0}}{c_{2,0}} \right)^{\frac{1}{b_2}} \end{aligned}$$

This gives the number of SMR units you would need to build to reach cost-parity with the NPP. Note that this simplified equation can also be used to calculate how many units will need to be built to reach a specified cost target:

$$u_2 = \left(\frac{c_{target}}{c_{2,0}} \right)^{\frac{1}{b_2}} \tag{4.6}$$

We can also put this break-even point in terms of total capacity built, G, by multiplying the number of units by the unit-capacity s_2 of the SMR:

$$G = s_2 \left(\frac{c_{1,0}}{c_{2,0}} \right)^{\frac{1}{b_2}} \tag{4.7}$$

This gives the total capacity G of the SMR design that would need to be built to reach cost parity with the NPP. To understand how the break-even deployment is influenced by the different parameters of the small reactor, Figure 4-2 shows a sensitivity analysis for each parameter. I can see that the initial costs $c_{1,0}$ and $c_{2,0}$ are the most important parameters.

However, even large nuclear reactors may experience learning effects, especially modern Gen III+ designs built as part of standardized fleets. Therefore, I will next calculate the break-even deployment under the scenario where the large reactor also experiences learning, albeit slower learning than the SMR. First each learning curve must be formulated as a function of deployed capacity, rather than units, u, so I replace $u_1 = G/s_1$ and $u_2 = G/s2$, where G is the total capacity deployed for each reactor. Substituting these into Equations 4.4 and 4.5 gives:

$$c_{1,0}\left(\frac{G}{s_1}\right)^{b_1} = c_{2,0}\left(\frac{G}{s_2}\right)^{b_2}$$

We solve for the break-even deployment G:

$$\begin{aligned}
\frac{G^{b_1}}{s_1^{b_1}} &= \frac{c_{2,0}}{c_{1,0}}\frac{G^{b_2}}{s_2^{b_2}} \\
\frac{G^{b_1}}{G^{b_2}} &= \frac{c_{2,0}}{c_{1,0}}\frac{s_1^{b_1}}{s_2^{b_2}} \\
G^{b_1-b_2} &= \frac{c_{2,0}}{c_{1,0}}\frac{s_1^{b_1}}{s_2^{b_2}}
\end{aligned}$$

Which gives an analytical expression for the break-even deployment:

$$G = \left(\frac{c_{2,0}}{c_{1,0}}\frac{s_1^{b_1}}{s_2^{b_2}}\right)^{\frac{1}{b_1-b_2}} \tag{4.8}$$

The units of G will be the same as the units of s_1 and s_2 whether in kW, MW, or GW. This expression illustrates the complex interactions between the different parameters. Figure 4-2 provides a sensitivity analysis of the break-even deployment to the various parameters for the microreactor. Besides the FOAK costs, the learning rate for the small reactor has the largest effect.

However, Equation 5 considers $c_{1,0}$ and $c_{2,0}$ as independent variables, but there may be a relationship between the two - especially if they are similar technology - given by the scaling relation from Equation 1.

$$\frac{c_{1,0}}{c_{2,0}} = \left(\frac{s_1}{s_2}\right)^{n-1} \tag{4.9}$$

Employing this scaling relation into Equation 4-2, gives the following:

$$G = \left(\left(\frac{s_1}{s_2}\right)^{n-1} \frac{s_2^{b_2}}{s_1^{b_1}}\right)^{\frac{1}{b_2-b_1}} \tag{4.10}$$

which simplifies the break-even volume equation down to five variables: the sizes of each reactor, the learning rate of each reactor, and the scaling factor. It is difficult to understand the relative importance of each of these variables just by sight. Before I apply these three break-even equations to realistic ranges for each parameter, I perform a simple sensitivity analysis with results shown in Figure 4-2. The base case assumptions for the sensitivity analysis are that $c_{1,0} = \$5,500/kW, c_{2,0} = \$10,000/kW, s_1 = 1,100MW, s_2 = 50MW, LR1 = 5\%$, and $LR2 = 20\%$

I explore the implications of these three break-even equations using example sizes of an SMR and a microreactor. In the US, there are currently two SMRs going through licensing:

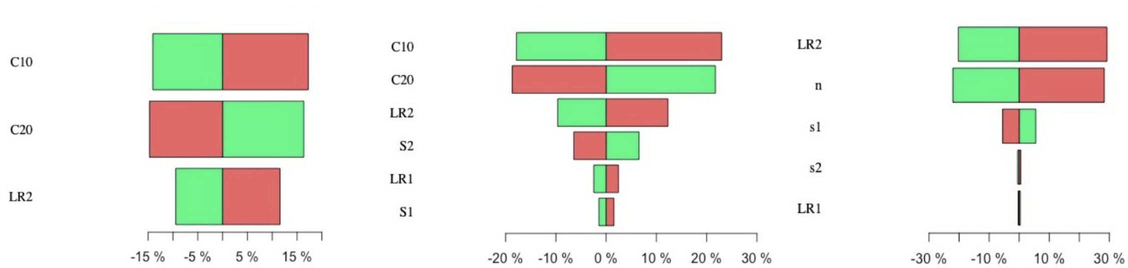

Figure 4-2: Sensitivity of the break-even deployment needed to reach cost parity between SMRs and large NPPs. Parameters are learning rate of microreactor (LR2), first-of-a-kind cost for the microreactor (C20), and capacity of the microreactor (s2) in MW. Green bars show a 5% increase in the parameter, and red bars shows a 5% decrease in the parameter. The base case assumptions for the sensitivity analysis are that $c_{1,0} = \$5,500/kW, c_{2,0} = \$10,000/kW, s_1 = 1,100MW, s_2 = 50MW, LR1 = 5\%$, and $LR2 = 20\%$

NuScale's 60 MW light-water reactor and Oklo's 1.5MW fast reactor. From our regression results, I can apply our range of scaling factors and learning rates to calculate break-even volumes needed to reach cost-parity with large LWRs under construction today. I can also use Equation 4.6 to calculate the break-even volumes needed to reach certain cost targets, say $\$2,000/kW$ as a function of reactor size, FOAK cost, and learning rate.

4.3 Results and Discussion

I ran regressions on each country's data. The results are presented in Table 4.2. First, it should be noted that almost no variables were significant for the France1, UK, and US1 data. This is likely because the number of reactors included for each was too small: 6, 16, and 16 respectively. As these reactors fleets were very early, primarily demonstrations, they may not be relevant for large fleets of commercial reactors in any case.

Across the rest of the country data sets, I find several commonalities. For every country except India and the U.K., the variable for reactor capacity was significant at least at the 99% level, and for most at the 99.9% level. The reason that reactor size was not significant for India could be that the country has mostly built reactors of the same small size, 200MW. The coefficient for the capacity variable was always negative, meaning that the per unit cost declined as the reactors size increased. The country experience variable was a significant correlate of cost at the 99.9% confidence level for every country, except only at the 99% level for India and South Korea. Country-level experience was not a significant variable for the early U.S. demonstration fleet. For every country except South Korea and the U.K., the coefficient for experience was positive, meaning that costs increased as each country built more reactors. While the effect size was smaller than for capacity, as both variables are measured in MW, a given country would increase their experience much faster than the average reactor capacity would change, so the overall impact of country experience would be greater. Lastly, the variable for number of reactors at each site was negative and significant at the 99% confidence level for all countries except the U.K., India, and German. For each additional reactor built at a site, the decline in cost would range from 4% for South Korea to 17% for the United States. The reason that the effect size for multi-reactor builds in the U.S. was larger than Korea is likely that almost every site in Korea is multi-reactor, with 4-8 reactors being common, while in the US, most sites only have 1-2 reactors.

To put these regression coefficients into more intuitive terms, I use the following equations: $n = \beta_{size} + 1$, $b = e^{\beta_{exp}}$, and $LR = 1 - 2^b$. Results are shown in Table 4.3 for the scaling factor and learning rates. A smaller scaling factor implies that scaling effects are large. Whereas a scaling factor equal to one means that there is no scaling effect. A reminder that the learning rate tells us how much the cost declined with every doubling of capacity deployed (or units deployed if the reactors are all equal in size).

From the historical cost data, it is clear that most countries did experience economies of scale in their large reactor fleets, from a scaling factor of -0.25 in West Germany to a factor of 0.77 in the US. However, these were across reactor fleets of very similar technology,

Table 4.2: Full Regression Results.

Variable	Canada	France	UK	India	Japan	Korea	US1	US2	Germany
lnCap	-1.253***	-0.461***	-0.216	-0.092	-0.297**	-0.529**	-0.234***	-0.742***	-1.253***
	(0.134)	(0.117)	(0.136)	(0.278)	(0.177)	(0.209)	(0.071)	(0.222)	(0.280)
lnLeadime	0.194	0.396***	0.432**	-0.093	-0.120	0.181	-0.090	1.197***	0.601*
	(0.231)	(0.105)	(0.147)	(0.031)	(0.227)	(0.167)	(0.221)	(0.146)	(0.221)
lnCountryExp	0.329***	0.135***	-0.388***	0.567**	0.312***	-0.092**	-0.149	0.302***	0.640***
	(0.087)	(0.034)	(0.075)	(0.186)	(0.049)	(0.039)	(0.094)	(0.058)	(0.0.137)
AtSite	-0.089***	-0.060***	-0.001	-0.164	-0.065**	-0.042***		-0.184***	0.058
	(0.018)	(0.013)	(0.027)	(0.080)	(0.031)	(0.013)		(0.053)	(0.140)
Constant	10.183***	8.711***	11.575***	4.210	7.246***	11.992***	10.041***	7.411***	9.230***
	(0.524)	(0.561)	(0.221)	(2.515)	(0.827)	(1.081)	(0.685)	(1.288)	(0.951)
n	24	59	22	18	57	21	16	113	23
R^2	0.809	0.512	0.97	0.486	0.494	0.872	0.510	0.723	0.770

$^{***}p < 0.001$, $^{**}p < 0.01$, $^{*}p < 0.05$

and it is unclear how well these scaling factors would apply to radically different types of advanced reactors and microreactors. More importantly, the historical data shows that almost every country experienced negative learning, such that costs rose with cumulative country experience. However, with large infrastructure constructed in place like the large reactors in this data set, it is difficult to achieve the same degree of learning that could be possible from serialized factory fabrication. Yet even with country-level learning rates, the regressions show positive learning rates of 6% for South Korea and 24% for the U.K.

From the literature review of regression analyses for historic nuclear construction, I find learning rates at the scale of the Architect-Engineering firm consistently around 10% for large-scale nuclear power plants; these studies mostly focus on the U.S commercial fleet. From the literature on costs of other energy technologies, I find learning rates as high as $35\% - 45\%$ for modular technologies like gas turbines and solar panels. For a more complex technology, offshore wind turbines experienced learning rates from $5\% - 20\%$ and coal plants from $6\% - 12\%$ (Rubin, Azevedo, et al. 2015). More broadly, I can use the relationship between unit size and learning rate from studies that aggregate learning rates and project for specific reactor sizes. For example, I can look at the line of best fit in Sweerts et al. (2020) and estimate that a 1MW SMR would have a learning rate of roughly 14%, whereas a 100MW SMR would have a slightly lower learning rate at 10%. If I look instead at the relationship found in Wilson et al. (2020), who looks at "de-scaled" learning which accounts for varying unit sizes, I would expect a 1MW reactor to have a learning rate of $5-10\%$, but a 100MW reactor might have a negative learning rate of a few percent.

Table 4.3: Estimated scaling factors and learning rates for historical nuclear reactor costs across countries, derived from our multi-factor regression model. A smaller value for n means that the reactors saw a larger effect from economies of scale. Values of n above 1 imply diseconomies of scale, i.e. reactors get more expensive as they get bigger.

Fleet	**Scaling Factor, n**	**Learning Rate**
Canada	0.21^{***}	$-26\%^{***}$
France	0.54^{***}	$-9.8\%^{***}$
India	$0.90^{\dagger}$	$-49\%^{**}$
Japan	0.7^{*}	$-24\%^{***}$
South Korea	0.47^{**}	$6.1\%^{**}$
United Kingdom	$0.78^{\dagger}$	$24\%^{***}$
USA1	0.77^{***}	$10\%^{\dagger}$
USA2	0.26^{***}	$-23\%^{***}$
West Germany	-0.25^{***}	$-55\%^{***}$

Note: *** indicates significance at the 99.9% confidence level, ** at the 99% level, * at the 95% level. † indicates insignificance at the 95% level.

Although the results show a large range of scaling factors across this new data, studies such as IAEA (2013) are clear that the scaling relationship is only appropriate for very similar designs, e.g. an SMR that is a scaled-down version of a large LWR. Past studies have drawn primarily on U.S. data, and thus primarily on LWR designs. Our historic data set includes a variety of designs, including LWRs, gas-cooled, and heavy-water reactors. Many SMRs in development are non-LWRs, that include high-temperature gas-cooled reactors, salt-cooled, metal-cooled, and fast reactors. Our historical scaling factors thus give a more robust approximation of boundary conditions on the range of FOAK costs for SMR and microreactors, relative to past studies that were restricted to LWR data. Even if there are economies of scale for the countries in this regression analysis, it is important to understand the limitations on the data that was included. Economies of scale effects were largest in Canada, but the range of capacities for reactors in the analysis was 200-800MW. Scaling effects were next largest in the U.S. commercial fleet, which ranged in size from 440-1300MW. There are two uncertainties here: 1) whether scaling effects apply above or below these size ranges, and 2) whether scaling effects are constant across the full range of unit size, or involve discontinuities. We know from the literature that there are many challenges with building larger and larger reactors, notably the increasing complexity of managing the safety of very large LWRs.

4.3.1 Application to Future SMRs

Using the full range of scaling factors from the historical data, $n = 0.2 - 0.8$, I can estimate the FOAK costs for two representative designs. Scaling the AP1000 cost down to a 60MW NuScale reactor would result in a FOAK cost ranging from $\$9,800/kW - \$56,000/kW$, depending on the scaling factor. The upper figure appears unreasonably expensive, even for the most over-budget nuclear projects worldwide. But the lower bound of roughly $\$10,000/kW$ is also much higher than NuScale's own estimate of $\$4,400/kW$ (NuScale 2020), which is actually less than the realized cost of the AP1000. For an even smaller reactor, Oklo's 1.5MW reactor, the scaling relation results in an even higher figure: $\$21,000/kW - \$1.1m/kW$, depending on the scaling factor. Of course, this scaling relation was meant to apply to similar technologies, and Oklo is a very different reactor than the AP1000. Even NuScale's LWR is likely too dissimilar to make a scaling relation applicable.

Next I look at how a reactor's cost might decline with a simple learning curve, given the range of learning rates from the literature. First, I plot the learning curve for a generic reactor technology that starts with a First-of-a-kind cost of $\$6,000/kW$ and experience learning rates ranging from $1\% - 25\%$. The results are shown in Figure 4-3. I also look at the same simple learning curve, but this time varying the FOAK cost and assuming a learning rate of 10%. These results are shown in Figure 4-4.

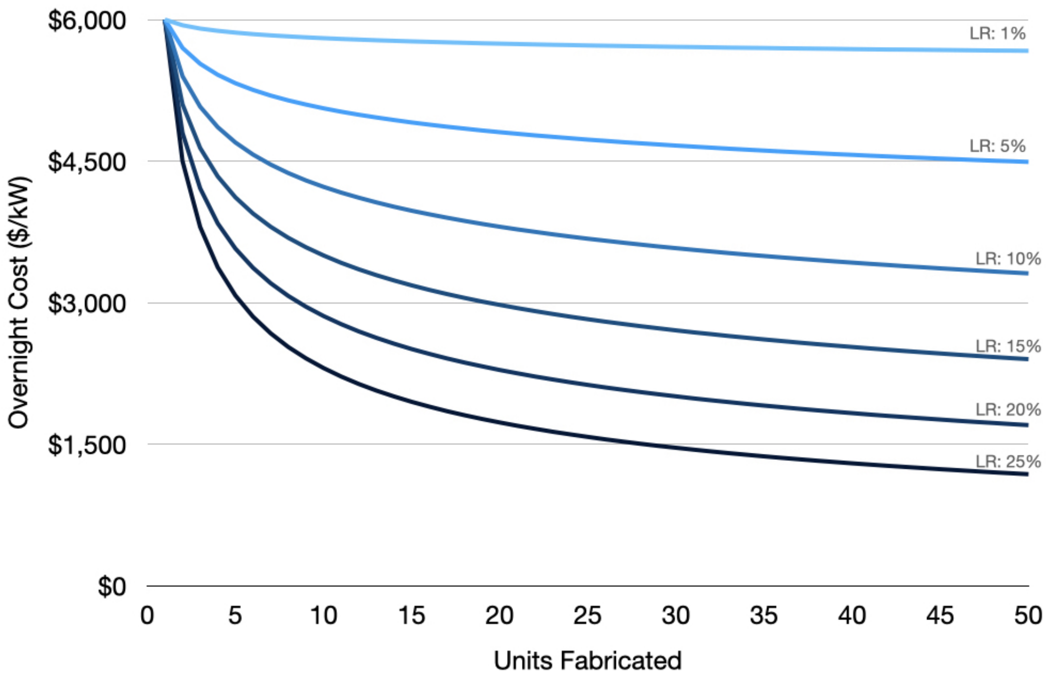

Figure 4-3: Learning curves for a generic SMR as a function of units fabricated and learning rate. The FOAK cost for all curves is $\$6,000/kW$.

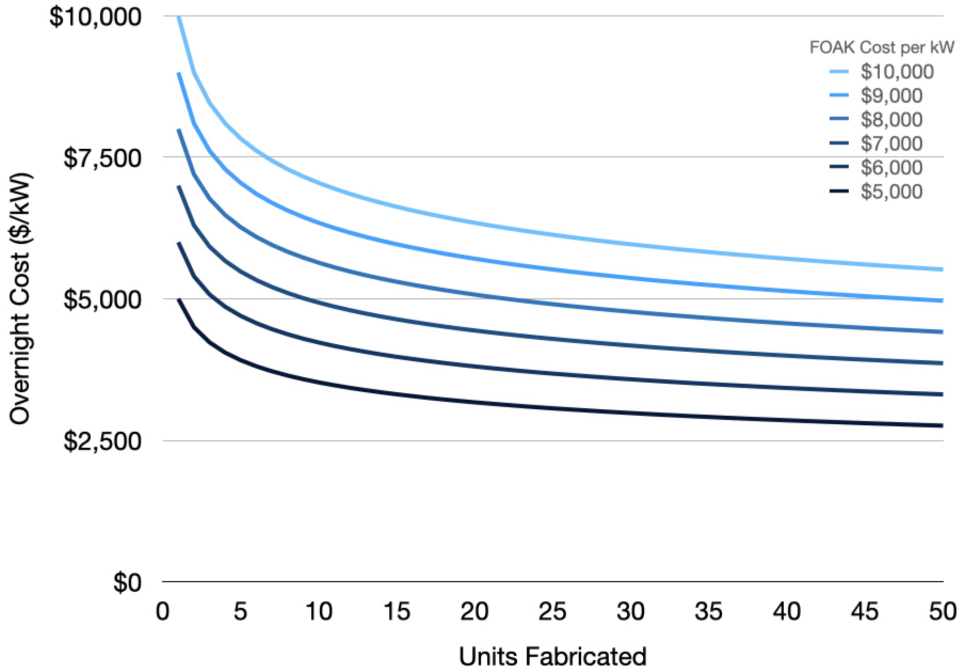

Figure 4-4: Learning curves for a generic SMR as a function of units fabricated and starting cost. The learning rate for all curves is 10%.

It appears that changes in learning rate have a much larger influence on cost trajectory than the initial cost. To understand the total cost implications of different learning rates, I also look at cumulative cost to deploy a fleet of SMRs with different learning rates. The results are shown in Figure 4-5 for a generic reactor with a FOAK cost of $\$6,000/kW$ and learning rates ranging from 1% (essentially no learning effects) and 25%. The difference in cumulative cost due to learning rate is striking. Here I show the cumulative cost as a function of units built, but I can convert to a total cost for different sizes of reactors. For example, the total cost to build 50 units of a 60MW reactor would be $17billion at a 1% learning rate, but only $6billion with a 25% learning rate. The difference in average reactor cost of the 50 unit fleet is $\$5,700/kW$ with 1% learning rate and only $\$1,900/kW$ with a 25% learning rate.

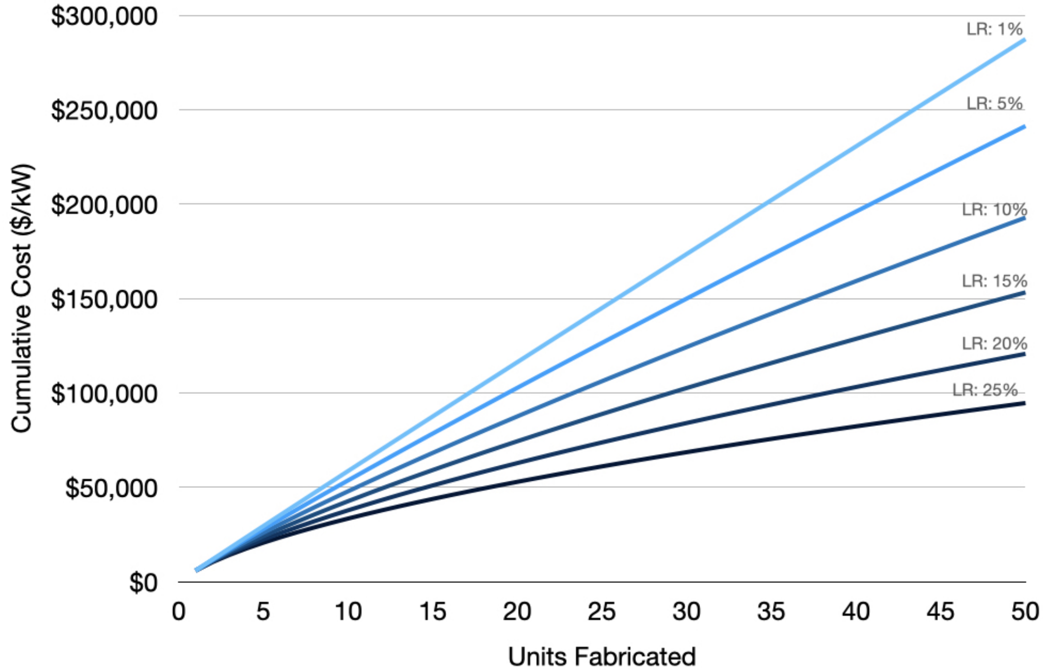

Figure 4-5: Cumulative cost to deploy a given number of SMRs as a function of learning rate. The starting cost is $\$6,000/kW$.

Lastly, Figure 4-6 shows the number of SMRs that would have to be built to reach a specific cost target of $\$2,000/kW$. The required deployment is calculated as a function of starting cost and learning rate. For an SMR with a FOAK cost of $\$5,000/kW$, fewer than 200 units would have to be built before the cost drops below $\%2,000/kW$ with learning rates above 10%. With a learning rate of 30% fewer than 10 units would need to be built before costs drop below $\$2,000/kW$. Note that these break-even deployment figures are independent of unit size. For a 1MW reactor, 10 units is only $10MW$, and for 100 units, that is still just $100MW$. For a 10MW or 100MW reactors, 10 units will translate to $100MW$ and $1,000MW$ respectively.

In reality, even the large reactor may experience some learning-by-doing, especially if I am considering learning at the A-E firm level, or if more countries move toward a single, standardized design for their large reactor fleet. Using Equation 4.8 for the break-even

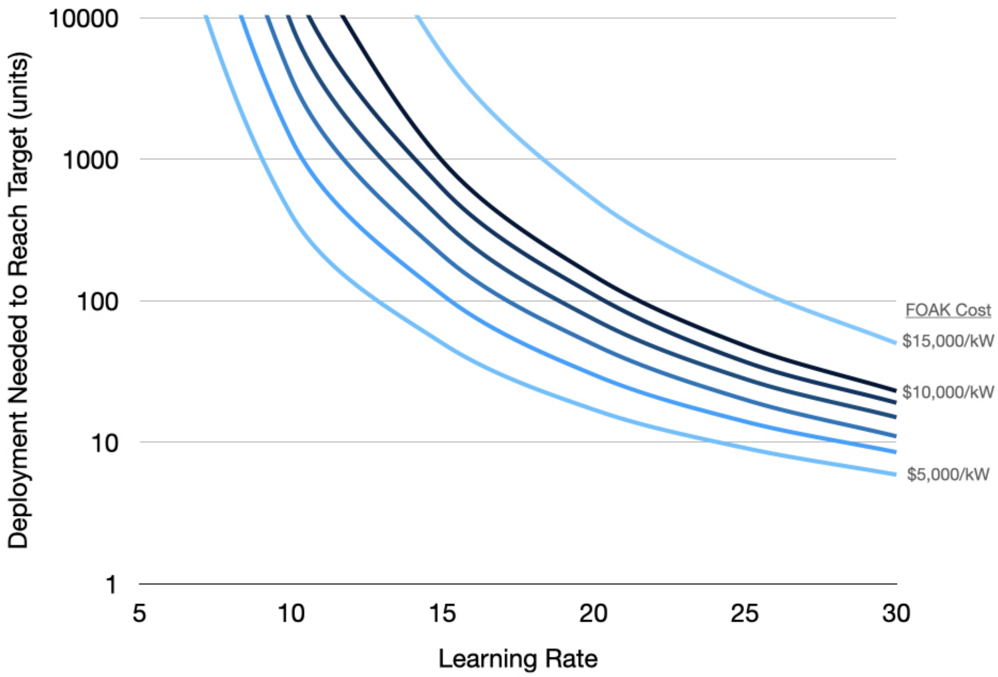

Figure 4-6: Volume of reactors necessary to reach a cost target of $\$2,000/kW$ as a function of learning rate and FOAK cost.

deployment assuming both reactors experience learning, I calculate how much capacity of a specific SMR would need to be deployed to break even with the cost per kW of a large reactor. I calculate the break-even volumes needed for two reactors - a 1.5MW microreactor and 60MW SMRs both starting at $\$11,000/kW$ - to reach cost parity with a 1,100MW reactor starting at $\$5,500/kW$ and experiencing a 1% learning rate. The results are shown in Figure 4-7. For the 60MW reactor, more than 1GW (over 16 units) would need to be built to reach cost-parity with the AP1000 if the learning rate is below 15%. However, for the 1.5MW reactor, only 100MW of capacity needs to be built to reach cost-parity if the learning rate is below 10%. At 25%, the break-even deployment needed for the microreactor is under 10MW, or less than 7 units.

Finally, I explore the trade-offs between learning effects and economies of scale, in situations where scaling applies. The examples above assume that the FOAK costs for the

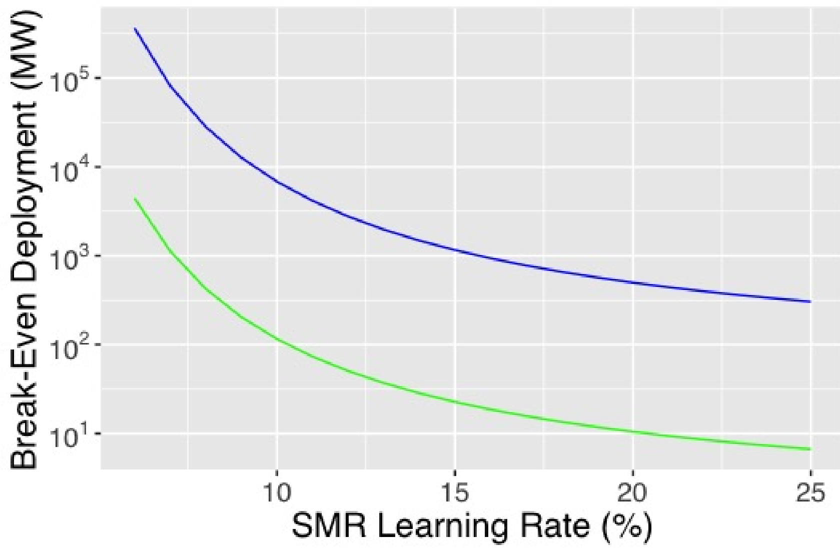

Figure 4-7: SMR deployment needed to reach cost-parity with an AP1000 reactor, assuming it starts at $\$5,500/kW$, 1,100MW and a learning rate of 1%. The break-even deployment is shown as a function of learning rate for the 60MW reactor (in blue) and the 1.5MW reactor (in green), assuming both start at $\$11,000/kW$.

SMRs are independent of the large LWR. This may be true for many types of advanced nuclear. But I use Equation 4.10 to calculate the SMR deployment needed assuming both economies of scale and economies of volume are in play. Here, I assume that the SMR is a perfect scaled-down version of the larger LWR, and look at two hypothetical sizes: 100MW and 10MW. For comparison, the large LWR is assumed to be 1,100MW with a FOAK cost of $\$5,500/kW$ and a learning rate of 1%. Table 4.4 provides the break-even deployment needed for each SMR size.

Again, in this example I assume that the SMRs are a true scaled-down version of the large LWR and that economies of scale apply. In this case, even with minimal (1%) learning for the large LWR, the amount of SMRs that would be needed to be built before their cost would break-even with that of the large reactor is quite large and depends significantly on the learning rate. For example, if there are strong economies of scale ($n = 0.2$) then even if the SMR experiences learning at a rate of 25%, the SMR would not reach cost parity

Table 4.4: Number of SMR units needed to be deployed to break-even on cost with a large LWR, assuming the large reactor is 1,100MW has a starting cost of $\$5,500/kW$ with a 1% learning rate. Break-even volumes are presented as a function of learning rate for the SMR, scaling factor, and for two different sizes of SMRS: 100MW and 10MW.

Scaling Factor	n=0.2		n=0.5		n=0.8		n=0.9	
Learning Rate	100MW	10MW	100MW	10MW	100MW	10MW	100MW	10MW
5%	–	–	–	–	1,800	–	4	17
10%	–	–	4,800	–	25	570	2	3
15%	5,200	–	200	32,000	8	53	1	2
20%	500	–	44	1,700	4	17	1	2
25%	110	10,000	18	300	3	9	1	2
30%	43	1,600	10	95	2	6	1	1

with the large reactor until 110 100MW units were built (11GW) or 10,000 10MW units (100GW).

This highlights an important insight: all studies of economies of scale in commercial nuclear power have been over a comparatively narrow range of capacities. For this analysis, the median reactor capacity was 700MW for Canada, 1200MW for West Germany, 900MW for France, 850MW for Japan, and 900MW for the U.S. commercial fleet. Economies of scale may apply when reactor designs remain similar, but the effect may not be linear. Put another way, economies of scale may not be continuous when extrapolating to very small or very large reactors, even if the design remains the same. And, of course, , it is very unlikely that the design stays similar at very small and very large sizes. Very large reactors require additional safety systems to manage the large amount of decay heat that remains after the reactor shuts down. Very small reactors can take advantage of passive safety features to simplify their design overall, reducing the number of redundant safety systems.

4.4 Conclusion and Policy Implications

Predicting the cost of future nuclear power plants has historically been plagued with overly optimistic assumptions. Engineers thought that economies of scale would justify larger and larger plants, and that innovation would bring improved performance and economics. The reality was that larger plants became increasingly complex, which led to construction delays, supply-chain disruptions, and an ever-changing regulatory environment. This explains why regression analysis finds economies of scale when analyzing overnight costs, but no economies of scale when looking at total costs. Equally important, the sheer diversity of designs paired with a diversity of owners and contractors - particularly in the U.S. and Japan - have precluded any meaningful learning effects, especially when incentives for cost-containment were removed through inefficient contracting.

Building small and very small nuclear reactors in a factory setting would be an entirely novel production process for this technology, and it is hard to predict how the costs will evolve. However, this theoretical exploration provides some insights. First of all, if economies of scale do apply to SMRs, they will likely end up being too expensive to ever be cost-competitive with large reactors, let alone other sources of power. However, there is little evidence that SMRs and especially microreactors are similar enough to traditional LWRs to suffer diseconomies of scale. These new reactors have been designed from scratch, taking advantage of simplifications in engineering and operations due to their small size. Even if SMRs start out being more expensive in terms of $/kW, even twice as expensive per kW, they can still reach cost-parity with the large LWR quickly with size-appropriate learning rates. Even for large LWRs, we see historic learning rates of roughly 10% at the level of the Architect-Engineering firm. For other comparable modular energy technologies, we see positive learning rates from $20\% - 30\%$.

Applying these learning rates to different sized SMRs, I find that an SMR could reach cost-parity with a large LWR after only a few dozen units are built, even if it starts at twice the per unit cost. Reaching a specific cost target, such as $\$2,000/kW$ is also feasible at learning rates above 15% with smaller SMRs. However, it would be a mistake to think that economies of scale and learning effects are inevitable or intrinsic to a given technology. For example, Breetz, Mildenberger, and Stokes (2018) analyzes the effects of politics and policy on learning curves for energy technologies at different levels of maturity, i.e. at different points in their learning curves. They argue that both components of experience curves — cost and deployed capacity — are politically constructed, and that political institutions and policies can serve to nurture emerging technologies in niche markets but also establish barriers to new technologies and protect incumbent technologies. Even successful technologies may need new and different political coalitions as their deployment moves from niche markets to mainstream. More work needs to be done to understand how policies could affect the learning rates for future SMRs.

Policies in support of SMR deployment will likely be needed both on the supply and demand side. While the ultimate goal of SMR and microreactor vendors may be full factory fabrication, the first few units will likely be built on site. These first-, second-, and third-of-a-kind costs may be much higher than the eventually factory fabricated units. For example, Rubin et al. (2006) found that costs and cost projects for two different emissions reduction technologies for coal power plants - Flue gas desulfurisation (FGD) Selective catalytic reduction (SCR) - were much lower than the first commercial deployment (Rubin, Antes, et al. 2006). Yet this example may not be applicable to fully modular technologies like SMRs. Still, policies to support demonstration and deployment of SMRs should build in resiliency to higher FOAK costs. This could include direct government procurement, public-private partnerships for demonstrations, and loan guarantees for manufacturing facilities.

More importantly, vendors will likely need tens of reactors in order to justify the investment in factory facilities to manufacture modular reactors. For comparison, Boeing and Airbus have a few hundred orders in place for new aircraft before the first one rolls off the assembly line (Lovering, King, and Nordhaus 2017). Federal policy that stimulated demand is ultimately what led to large cost declines for solar technologies (Nemet 2006). Similar policies should be implemented for small and microreactors, such as production and investment tax credits, federal Power Purchase Agreements, state-level clean energy mandates, and a streamlined licensing process for modular reactors.

Chapter 5

Conclusion and Policy Implications

I started this work with two main questions about the future of the U.S. nuclear industry: 1) what are the international security and other implications of a shift away from the U.S. as the dominant exporter of nuclear technologies, and what can be done to reverse that trend, and 2) how might a future with small-scale, distributed nuclear impact the global energy transition?

From our work in Chapter 2, there was broad agreement among technology and national security experts on our diagnosis of the problem, but a surprising amount of disagreement on the potential solutions. Experts who participated in the workshop agreed that the strength of the U.S. commercial nuclear industry has played a significant role in facilitating U.S. leadership in international control regimes. They also believed that, with diminished presence in civilian nuclear power, U.S. influence with respect to these regimes is likely to decline—particularly for the next generation of nuclear technologies.

When asked to evaluate the efficacy and feasibility of six proposed strategies that might be adopted to enhance U.S. influence internationally, along with four additional strategies the experts had developed during the workshop, two strategies emerged as above median feasibility and efficacy over the next 15 years: the creation of a U.S.-South Korea Consortium to build new power projects and progress on addressing the problem of U.S. domestic nuclear waste. Progress on nuclear disarmament, adoption of a NASA Model involving support for private reactor developers, and internationalizing the nuclear fuel cycle were assessed to be highly effective strategies that are also unlikely to be implemented. The efficacy of the two diplomatic strategies was deemed low, but their feasibility fell above the median for the set. The lowest ranked strategies in terms of efficacy were developing a U.S.-based consulting organization for countries aspiring to build their first nuclear power plant, reforming the nation's export control system, and building an International Technology Development Center. The latter two also ranked below the median for feasibility, suggesting that policy makers should think carefully, and perhaps make refinements, if they were to choose to pursue their development and implementation. The most surprising result here was that our experts did not agree with the conventional wisdom that the main obstacle to strong U.S. nuclear exports was overly strict export controls. Simply put, they did not think that U.S. nuclear vendors had or could have a commercially viable product to sell.

However, most of our experts were still thinking about civilian nuclear power in terms of large-scale projects that are constructed on site, which necessitates serious state support to be cost-competitive and without subsidy is untenable in any deregulated power market. Even when we discussed advanced nuclear technologies, most experts assumed these designs were decades from commercialization and would require unprecedented federal funding to be demonstrated. Yet as our review in Chapter 3 suggests, SMRs and especially microreactors could be closer to commercial deployment that most assume, and require smaller amounts and more targeted forms of federal support. That said, there is still a need to demonstrate the technology domestically before it could be an attractive export product, and, at least at the outset, would likely require a focus on niche markets.

To this end, the case studies of microgrids that I performed in Chapter 3 show that microreactors could be cost-competitive with diesel generators for certain applications where diesel costs are high or reliability is mission-critical. Today no form of nuclear at any scale is cost-competitive with grid electricity in the U.S. For nuclear to be cost-competitive for on-grid microgrids, the capital cost together with $O\&M$ costs will need to be reduced by at least 25%, and low-cost financing will be required. Even then, microreactors may not be cost-competitive without a carbon price or reliability payment.

The LCOE for microreactors is most sensitive to the initial capital cost. In order to reach cost-parity with grid electricity, costs would need to drop below $2,000/kW. It is difficult to predict what SMRs and microreactors will cost, especially the FOAK plants, and there is good reason to be skeptical of optimistic cost projections of future nuclear (Koomey and Hultman 2007). At the same time, there is also reason to be skeptical of those relying on traditional economies of scaling relations to make the case that SMRs will be too expensive to matter (IAEA 2013; Moore 2016; Froese, Kunz, and Ramana 2020).

In Chapter 4, I explored the cross-over between economies of scale and economies of volume (i.e. learning-by-doing) to understand the future cost evolution of small and very small, factory-fabricated nuclear technologies. Most importantly, if historic economies of scale experienced by the nuclear industry do apply to SMRs, they will likely end up being too expensive to ever be cost-competitive. However, there is little evidence that SMRs and especially microreactors are similar enough to traditional LWRs to suffer diseconomies of scale. These new reactors have been designed from scratch to take advantage of simplifications in engineering, manufacturing, and operations made possible by their small size. Even if SMRs start out being more expensive, even twice as expensive per kW, they can still reach cost-parity with the large LWRs quickly with size-appropriate learning rates. Even for large LWRs, we see historic learning rates of roughly 10% at the level of the Architect-Engineering firm. For other comparable modular energy technologies, we see positive learning rates from $20\% - 30\%$.

Applying these learning rates to different sized SMRs, we find that an SMR can reach cost-parity with a large LWR after only a few dozen units are built, even if it starts at twice the cost. Reaching a specific cost target, such as $\$2,000/kW$ is also feasible at learning rates above 15% with SMRs on the smaller side. However, it would be a mistake to think that economies of scale and learning effects are inevitable or intrinsic to a given technology. For example, Breetz, Mildenberger, and Stokes (2018) analyzes the effects of politics and policy on learning curves for energy technologies at different levels of maturity, i.e. at different times along their learning curves. They argue that both components of experience curves — cost and deployed capacity — are politically constructed, and that political institutions and policies can serve to nurture emerging technologies in niche markets but also establish barriers to new technologies and protect incumbent technologies. Even successful technologies may need new and different political coalitions as their deployment moves from niche markets to mainstream. More work needs to be done to understand how policies could affect the learning rates for future SMRs.

The work in this dissertation highlights two areas where policy intervention could significantly help to accelerate global decarbonization while expanding energy access: 1) facilitating FOAK SMR and microreactor demonstration and stimulating demand for these technologies, and 2) laying the groundwork to leverage these technologies as valuable export products to strengthen U.S. international relations and strengthen global security standards.

5.1 Domestic Policy

Policies in support of SMR and microreactor deployment will likely be needed both on the supply and demand side. While the ultimate goal of SMR and microreactor vendors may be full factory fabrication, the first few units will likely be largely built on site. These first-, second-, and third-of-a-kind costs may be much higher than the eventually factory fabricated units. For example, Rubin et al. (2006) found that costs and cost projects for two different emissions reduction technologies for coal power plants - Flue gas desulfurisation (FGD) Selective catalytic reduction (SCR) - were much lower than the first commercial deployment. When developing policies that support demonstration and deployment of SMRs, government agencies could build in resiliency to higher FOAK costs. This might include direct government procurement, public-private partnerships for demonstrations, and loan guarantees for manufacturing facilities.

More importantly, vendors will likely need tens of reactors in order to justify the investment in factory facilities to manufacture modular reactors. For comparison, companies like Boeing and Airbus typically have several hundred orders in place for new aircraft before the first one rolls off the assembly line (Lovering, King, and Nordhaus 2017). Federal and state policy that stimulated demand played a major role in inducing the large cost declines for solar technologies (Nemet 2006). Similar policies could be implemented for SMRs and microreactors, such as production and investment tax credits, federal Power Purchase Agreements, state-level clean energy mandates, and a streamlined licensing process for modular reactors.

From our initial results, it appears that there may be a promising initial market for microreactors in niche markets such as isolated arctic communities that are experiencing high energy costs. Depending on the realized learning rates, the technology could become cheaper fast enough to compete with grid electricity. Oklo piloted a new, streamlined licensing process that will hopefully be faster, more efficient, and cheaper to complete – taking as little as 24 months. The next microreactor developers, and possibly larger advanced reactor designs, could also take advantage of this path that Oklo piloted. Whether it's a microreactor or a scaled-down version of a larger design, this streamlined process could allow for more iterative innovation and rapid demonstration. Even if microreactors don't come to dominate the nuclear sector, their accelerated licensing and deployment could demonstrate a diverse set of novel concepts from fuel to operations, leading to faster adoption of cost-saving innovations across the industry. More importantly, microreactors are being designed to serve new markets not currently served by nuclear power and difficult to decarbonize. Small-scale demonstrations could open more sectors to nuclear like direct industrial use, hydrogen production, and desalination, decarbonizing beyond the power sector.

Separate from advanced reactors, microreactors may need their own tailored policies to accelerate RD&D, drive demand, and determine appropriate regulation and financing schemes. Currently, the policy space is falling behind the commercialization timelines of some microreactor companies. If the U.S. government wants to support microreactor commercialization as part of a broader climate change agenda, they should work to develop policies that drive microreactors down the learning curve as well as promote them as an export to nuclear newcomer countries.

5.2 Policy to Strengthen U.S. Influence Internationally

If SMRs and microreactors can be successfully licensed and demonstrated in North American markets, they have the potential to become an attractive export product. However, there is still plenty of work that can be started now to ensure the U.S. leverages potential exports to strengthen its influence and international security regimes abroad. Most importantly, the U.S. should accelerate demonstration of SMR and microreactor designs so that the technology can be proven for future export markets.

Global demand for electricity will at least double by 2050, with the large majority of new demand coming from non-OECD countries (Kempfer et al. 2020). While only a few of these countries currently have nuclear power, most will have the capabilities to import commercial nuclear technologies by 2030. Russia and China are already engaging with many of these countries, even if commercial nuclear projects are decades away. Therefore, the U.S. could be more proactive in engaging with these nuclear newcomers by establishing bilateral cooperation agreements.

Of course, state-supported nuclear vendors in Russia and China can still offer many services that private nuclear companies in this U.S. cannot, putting U.S. suppliers at a competitive disadvantage. Commercial demonstration of advanced reactor technologies that have been licensed in the U.S. could help gain new access to the global market, but more targeted support for export projects will be needed. For example, the U.S. International Development Finance Corporation (DFC) recently ended its prohibition on funding nuclear projects. While DFC funding could help a small number of U.S. nuclear vendors, the government could leverage its influence in international development banks to change their longstanding policies against financing nuclear as well. This could help U.S. companies compete against countries like Russia, China, and South Korea that often offer generous financing packages.

Microreactors in particular offer novel opportunities for deployment and business models, and these could be demonstrated in partnership with potential host countries. For example, very small reactors could facilitate a complete Build-Own-Operate-Remove business model, where the entire reactor is replaced with a new one and the old one is sent back to the country of origin for decommissioning or refueling. This would eliminate the need for fuel production and handling in host countries. Similarly, many aspiring nuclear countries will face severe water stress in the next decades, and could prove fertile ground for demonstrating a microreactor paired with a desalination plant.

However, the U.S. could also use potential leadership in advanced nuclear to revitalize international nuclear security regimes. Since the U.S. is currently leading in the number and diversity of advanced nuclear companies, the federal government could consider increasing funding to send experts through the IAEA, to leverage expertise in non-LWR technologies to develop modern safety and security standards. Moving beyond a unidirectional export model, the U.S. could also explore opportunities to partner with newcomer countries on reactor development and demonstration. Such knowledge-sharing programs could include professional exchange programs, funded graduate programs, as well as funding for the Nuclear Regulatory Commission to work with emerging nuclear countries to strengthen their own regulations.

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Appendix A

Appendices for Chapter 2

A.1 Other OECD Countries and Use of Nuclear as Leverage

Canada

While, in terms of population, it is a smaller country without nuclear weapons, Canada has been able to maintain significant leadership in nuclear security through its nuclear trade. Canada has historically been the third largest exporter of commercial nuclear reactor technology, and they had a particular focus on emerging economies (Bratt 2006). Most notably, in the post- war period, Canada was involved in a series of UN commissions on nuclear weapons, alongside the major nuclear powers the U.S., U.S.S.R, Britain, and France. Canada would not have been invited except for its leadership in nuclear technology (Levitt 1993). Yet, Bratt (2006) argues that Canada's exports were more motivated by economic considerations for its domestic industry and a desire for more general political influence, not directly focused on nonproliferation.

Canada's exports of the CANDU reactor have been an explicit and critical tool of their foreign policy, particularly the two goals of aiding economic development in emerging economies and containing the spread of communism (Bratt 2006). Canada has exported to Argentina, China, India, Korea, Pakistan, and Romania. Sometimes Canada's political motivations worked against the international nonproliferation agenda. In the 1950s, Canada's politicians argued strongly for nuclear exports to India to strengthen their relations (Fuhrmann 2013). Ultimately, the plutonium used in India's first atomic weapons came from a Canadian-supplied reactor. Canada also offered "sweeteners" to its nuclear trade deals, such as non-nuclear exports like aircraft but also relaxations of nuclear safeguards. Such sweeteners are now prohibited under Nuclear Supplier Group rules (Bratt 2006).

France

Although France has been a major force in commercial nuclear power, historically second only to the U.S., it has had a different role in international control regimes. Although France was involved in the formation of the Nuclear Suppliers Group, they refused to become a member, because of a concern that the group would appear to be ganging up on non-NPT and non-weapons countries (Lellouche 1983). France originally refused to sign the Non-Proliferation Treaty, but was eventually acceded into the treaty in 1992. France was also at odds with the U.S. for several decades over reprocessing technology and fast breeders, over which the U.S. wanted stricter control (Yager 1981). France has exported eleven commercial reactors in total to China, Spain, South Korea, and South Africa.

Great Britain

Despite Britain's early entry in nuclear power and long history as a colonial power, the country did not focus on nuclear exports as a tool of political influence abroad. Much like Canada, the UK was forced to develop their own nuclear technology after the war, and settled on gas-cooled reactors. That the technology gained a reputation for poor performance and high costs may have led to limited exports (Yager 1981). Unlike the other major nuclear vendors, a single leading company did not emerge in the UK as a flagship exporter. Domestic nuclear power plants were built by a series of industrial consortia until 1973 when the National Nuclear Corporation (NNC) was formed (Robert Boardman 1983), but this was at the trailing end of the nuclear power boom.

Britain's colonial history did guarantee some leverage in nuclear regimes. As India was a British Commonwealth, Britain often had a seat at the table if India was involved (ibid.). But as a nuclear weapons state, with a nuclear navy, and a permanent member of the UN Security Council, Britain still retained much influence on the structure of these regimes, if not their implementation through nuclear trade. The UK has only exported two commercial reactors, both gas-cooled designs, to Japan and Italy. Both reactors have since been shut down. However, they do have significant operational experience with gas-cooled reactors, and could leverage that in the future if that technology makes a comeback.

A.2 Literature Included in Background

The literature we reviewed to understand the connection between commercial nuclear trade and influence on foreign security standards was focused on the following:

Blackwill, R. D. & Carnesale, A. New Nuclear Nations: Consequences for U.S. Policy. (Council on Foreign Relations, 1993).

Boardman, R. The Politics of Fading Dreams: Britain and the Nuclear Export Business. in Nuclear Exports & World Politics (eds. Boardman, R. & Keeley, J. F.) (St. Martin's Press, 1983).

Boardman, R. & Keeley, J. F. Nuclear Export Policies and the Non-proliferation Regime. in Nuclear Exports & World Politics (eds. Boardman, R. & James F. Keeley) (St. Martin's Press, 1983).

Fuhrmann, M. Exporting Mass Destruction? The Determinants of Dual-Use Trade. J. Peace Res. 45, 633–652 (2008).

Kapur, A. Nuclear Energy, Nuclear Proliferation and National Security: Views from the South. in Nuclear Exports & World Politics (eds. Boardman, R. & Keeley, J. F.) (St. Martin's Press, 1983).

Schiff, B. N. International Nuclear Technology Transfer: Dilemmas of Dissemination and Control. (Croom Helm, 1984).

The Nuclear Renaissance and International Security. (Stanford University Press, 2013).

Walker, W. & Lönnroth, M. Nuclear Power Struggles. (George Allen & Unwin Ltd., 1983).

Yager, J. International Cooperation in Nuclear Energy. (The Brookings Institution, 1981)

To assist in the development of our set of six strategies that might be used to increase influence by the U.S. and others in global nuclear governance, we drew primarily from the following:

Aumeier, S. & Allen, T. How to Reinvigorate US Commercial Nuclear Energy. Issues Sci. Technol. (2017).

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A.3 List of Workshop Participants

Table A.1: List of workshop participants and how we classified experts who participated in the workshop.

Nuclear Security Experts	Nuclear Energy Experts
Rachel Bronson	Todd Allen
Sue Clark	Rita Baranwal
Steve Fetter	Matthew Bowen
Charles Ferguson	Ashley Finan
Corey Hinderstein	Carey Haas
Laura Holgate	Joseph Hezir
Micah Lowenthal	Michael Ford
Nicholas Miller	Kate Jackson
Sharon Squassoni	John Kotek
Mitch Wallerstein	Richard Meserve
	Sola Talabi

A.4 Workshop Pre-Readings

Prior to the workshop we assembled a book of pre-readings which consisted of copies of the following:

The U.S. civilian nuclear enterprise

- M. Granger Morgan, Ahmed Abdulla, Michael J. Ford, and Michael Rath: "US nuclear power: The vanishing low carbon wedge," Proceedings of the National Academy, 2018.
- Matt Bowen: Executive Summary and Recommendations from "Part 810 Reform: Improving the Efficiency of U.S. Export Controls for Nuclear Energy Technologies," Nuclear Innovation Institute, 2017.
- Steven E. Aumeier and Todd Allen: "How to Reinvigorate US Commercial Nuclear Energy" Issues in Science and Technology," Winter 2018.
- Ahmed Abdulla, Michael J. Ford, M. Granger Morgan, and David G. Victor: "A retrospective analysis of funding and focus in US advanced fission innovation. Environmental Research Letters, 12(8), 084016. 2017.
- Michael J. Ford, Ahmed Abdulla, M. Granger Morgan, David G. Victor, "Expert Assessments of the State of U.S. Advanced Fission Innovation," Energy Policy, 108, 194-200, 2017.

The status of U.S. influence in the global civilian nuclear enterprise:

- CSIS: Executive Summary from "Restoring U.S. Leadership in Nuclear Energy," Center for Strategic and International Studies, 2013.
- Energy Futures Initiative: Introduction and Report Summary from "The U.S. Nuclear Energy Enterprise: A Key National Security Enabler, Energy Futures Initiative Inc., 2017.
- Robert F. Ichord: "US Nuclear Power Leadership and the Chinese and Russian Challenge," Issue Brief, The Atlantic Council, 2018.
- Laura S. H. Holgate and Sagatom Saha, " America Must Lead on Nuclear Energy to Maintain National Security," The Washington Quarterly, Summer 2018.

Russia, China and the international nuclear civilian nuclear enterprise:

- Mark Hibbs: "A more Geopoliticized Nuclear Suppliers Group," Mark Hibbs: "A more Geopoliticized Nuclear Suppliers Group," Carnegie Endowment for International Peace, 2017.
- Siegfired S. Hecker: Table of Contents, Time Line and Overview from Doomed to Cooperate, 2016.
- Mark Hibbs: Table of Contents, About the Author, Summary, Conclusions and Outlook from The Future of Nuclear Power in China, Carnegie Endowment for International Peace, 2017.
- Alan Ahn: "A Vision for International Partnerships in Global Nuclear Power: Matching Russia' nuclear playbook in the middle east," Briefing from the Global America Business Institute, 2018.
- Madison Freeman: "How Russia, China Use Nuclear Reactors To Win Global Influence," Defense One Newsletter, July 13, 2018.
- Anton Khlopkov: "Russia Nuclear Security Policy: Priorities and potential areas of cooperation," Policy Analysis Brief, Stanley Foundation, 2015.

Control Regimes

- U.S. Department of State, Bureau of International Security and Nonproliferation (ISN): List of Treaties and Agreements, 2018.
- US Department of Commerce: Summary of Export Control Regulations, 2016.
- Council on Foreign Relations, International Institutions and Global Governance Program: Except from The Global Nuclear Nonproliferation Regime, 2012.

A.5 Rationales for New Strategies

Non-Profit Consulting Firm. The motivation for such an organization would be to aid and advise newcomer countries on their first commercial nuclear power projects. This organization could also help with research and medical reactors. This would go beyond standard IAEA advising to include help on reviewing commercial proposals and stronger support on broader grid and electricity development issues. The goal would be for an NGO that has credibility and objectivity, but that can rely on US expertise from both the nuclear industry and the electric power industry. Ideally, this organization would not be funded by a single nuclear supplier, but could be funded by the Nuclear Energy Institute or perhaps Department of Commerce, although partnership with the Nuclear Regulatory Commission, State Department, and Electric Power Research Institute would also be valuable.

Make progress on disarmament. The U.S. has a commitment to make progress on disarmament under Article VI of the Non-Proliferation Treaty. The lack of progress to-date on disarmament weakens U.S. standing in international safeguards negotiations, particularly with Russia, but also with non-aligned states. What exactly progress would entail is up for discussion, but any concrete policy would improve U.S. reputation and give more strength to U.S. demands for stricter non-proliferation standards in newcomer countries. Along these lines, the U.S. could also consider a push to ratify the Comprehensive Test Ban Treaty.

Domestic Waste Solution. The U.S. should restart efforts to develop a domestic solution to the back-end of the fuel cycle. This could keep the option open for fuel take-back from host countries. This would restore U.S. reputation and help level playing field with Russia's take-back programs in developing economies. The U.S. should follow the advice of President Obama's Blue Ribbon Commission and continue the Department of Energy process of consent-based siting for regional interim storage as a short-term solution.

U.S.-South Korea Construction Consortia. Consortium nuclear power plant builds between US and South Korea, either in US or third country. Joint builds in newcomer countries would appear to have the most leverage in influencing security standards. Such a consortia would bring together the successful Korean construction experience and manufacturing capabilities with the diplomatic power and regulatory expertise of the U.S. The U.S. was considering a consortium bid with the Japanese nuclear vendor Toshiba for Saudi Arabia's first nuclear power project.

A.6 Full Workbook Results

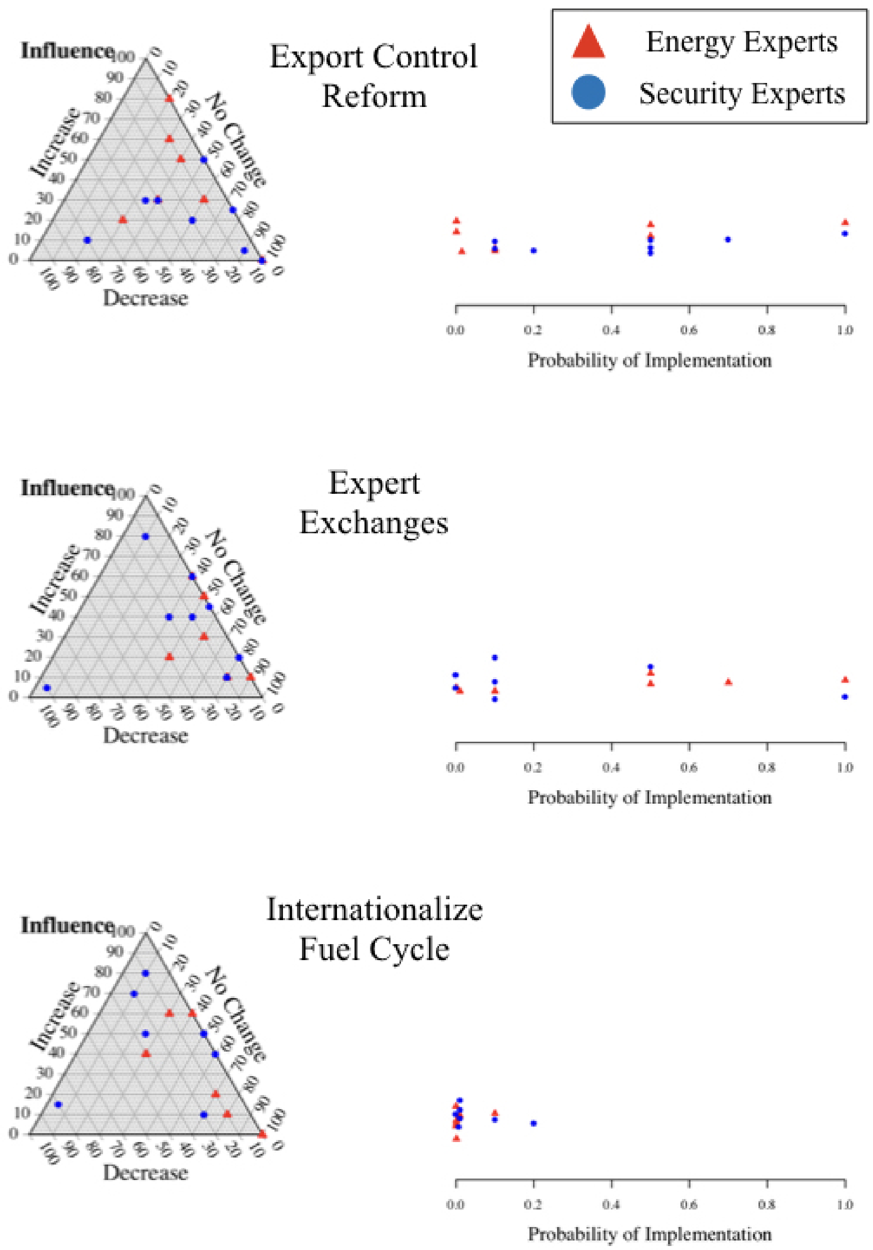

Figure A-1: Full results for the expert assessment of the effectiveness of each strategy to change U.S. influence over five years: increase U.S. influence, no change to U.S. influence, or a continued decline in U.S. influence. On the right we show how the experts rated the probability that each strategy could be implemented over the next five years.

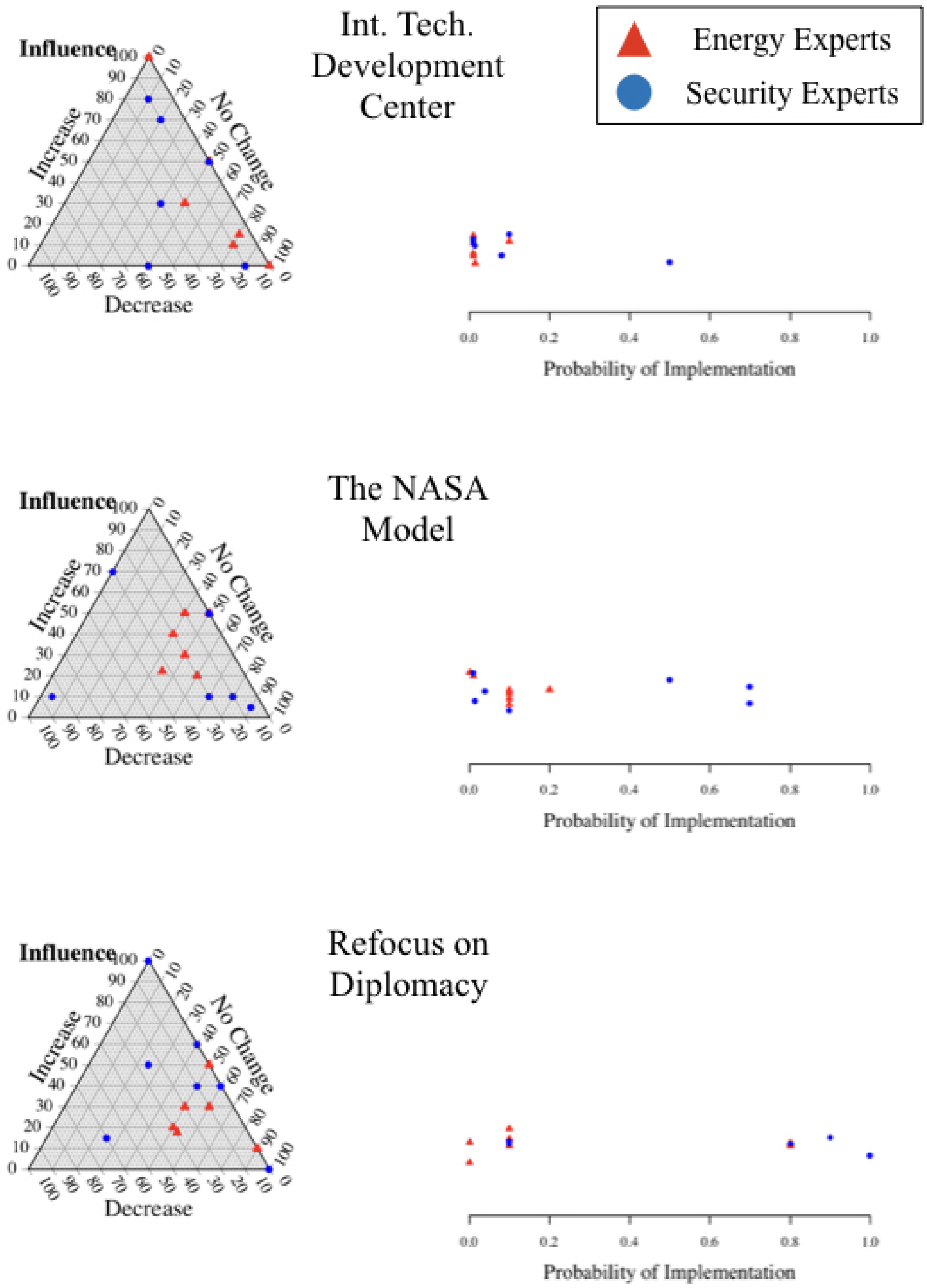

Figure A-2: Full results for the expert assessment of the effectiveness of each strategy to change U.S. influence over five years: increase U.S. influence, no change to U.S. influence, or a continued decline in U.S. influence. On the right we show how the experts rated the probability that each strategy could be implemented over the next five years.

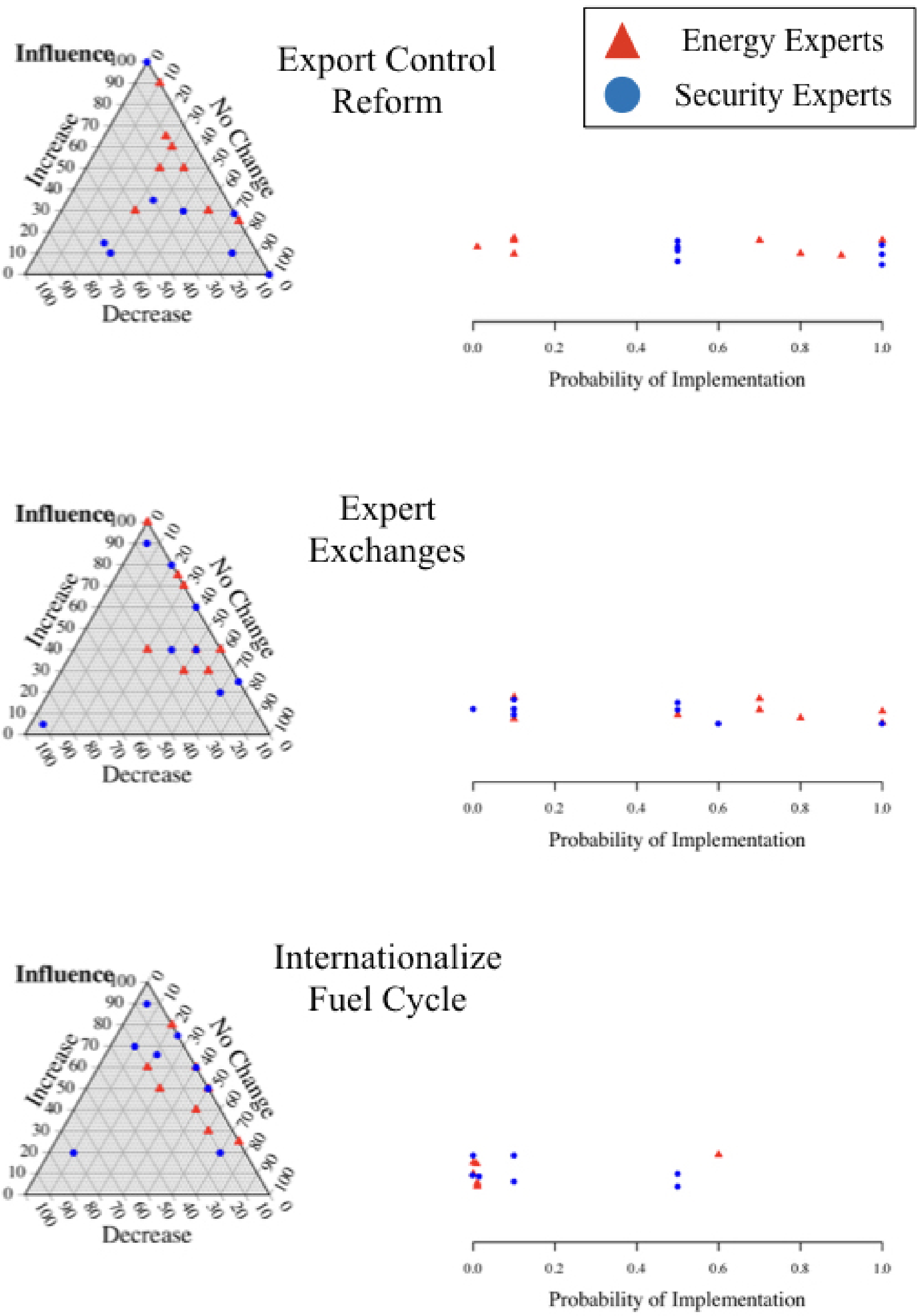

Figure A-3: Full results for the expert assessment of the effectiveness of each strategy to change U.S. influence over fifteen years: increase U.S. influence, no change to U.S. influence, or a continued decline in U.S. influence. On the right we show how the experts rated the probability that each strategy could be implemented over the next fifteen years.

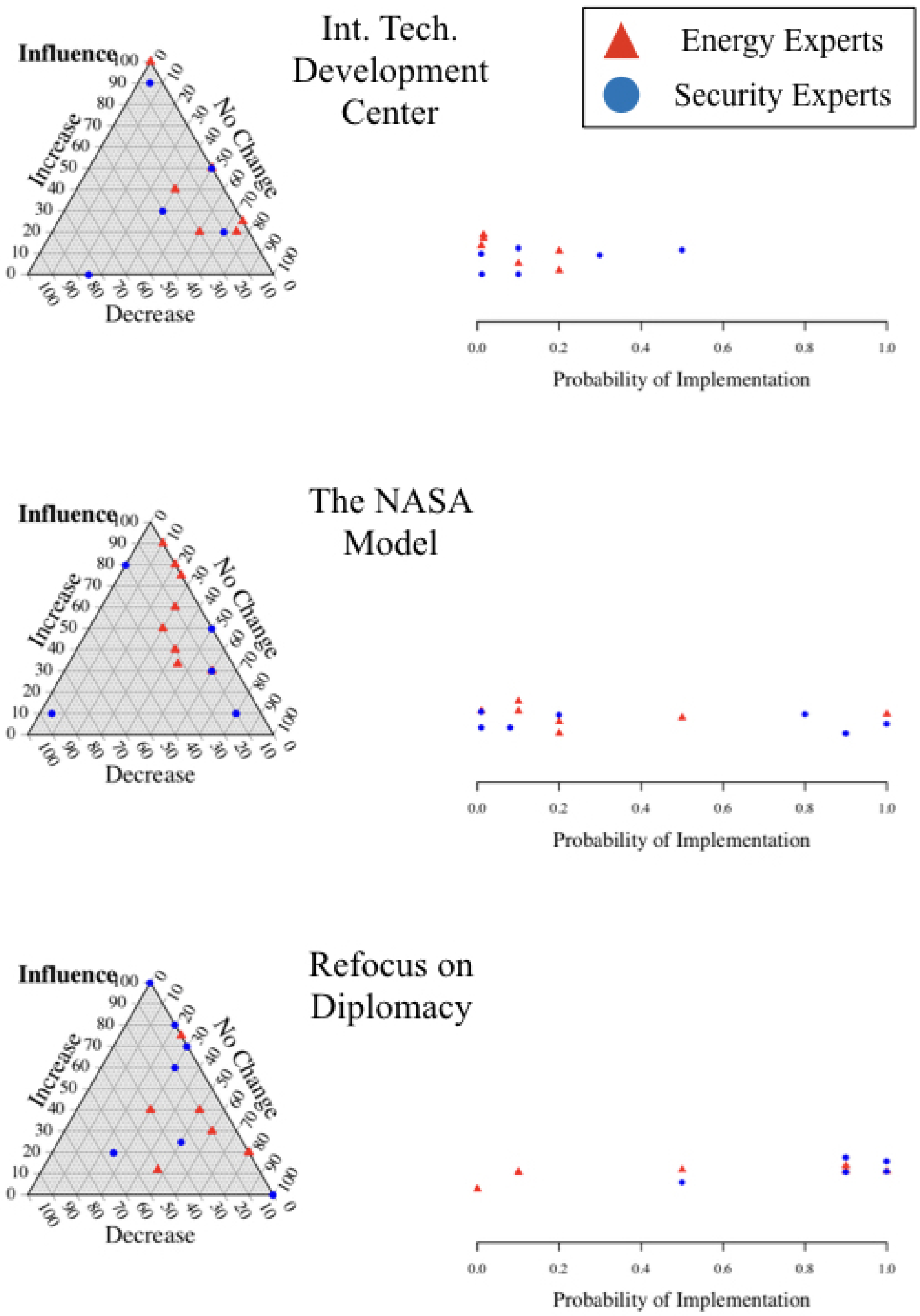

Figure A-4: Full results for the expert assessment of the effectiveness of each strategy to change U.S. influence over fifteen years: increase U.S. influence, no change to U.S. influence, or a continued decline in U.S. influence. On the right we show how the experts rated the probability that each strategy could be implemented over the next fifteen years.

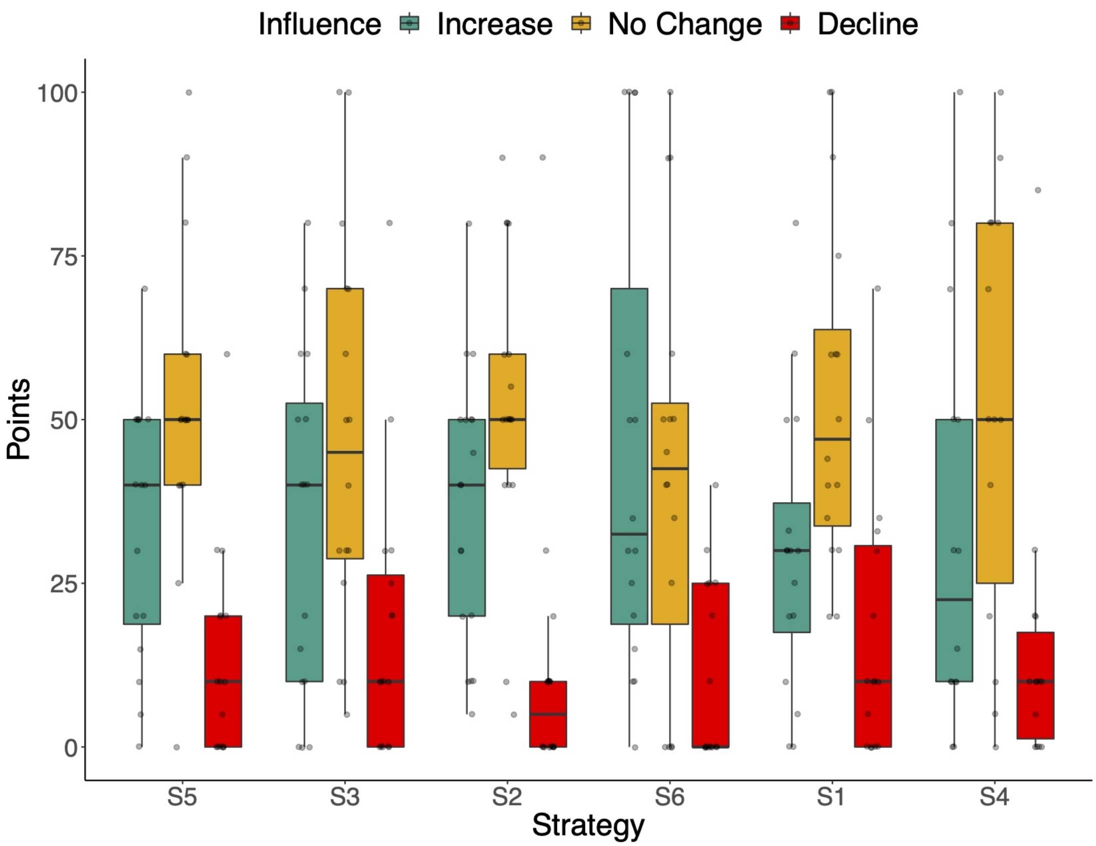

Figure A-5: Summary of how workshop participants allocated 100 points to three outcomes for each strategy over a 5-year time period: an increase in U.S. influence (green), no change in U.S. influence (yellow), and a decline in U.S. influence (red). The strategies are ordered from left to right by the median "increase in influence" score. The boxes extend to one quartile from the median, the whiskers extend 1.5 times the interquartile range, and dots show outliers that lie beyond the whiskers.

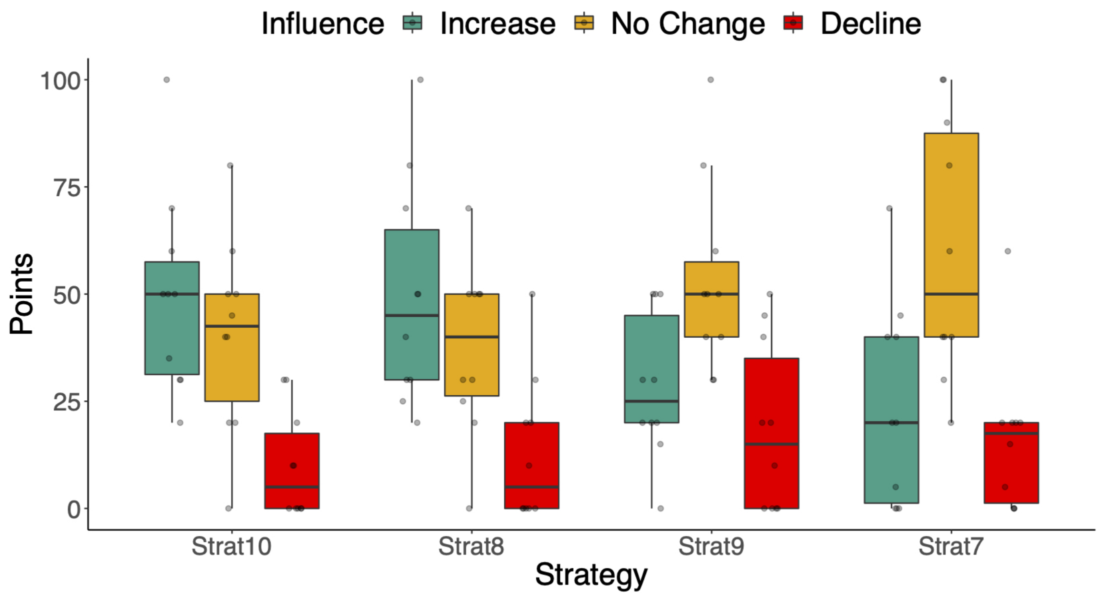

Figure A-6: Summary of how workshop participants allocated 100 points to three outcomes for each strategy over a 5-year time horizon: an increase in U.S. influence (green), no change in U.S. influence (yellow), and a decline in U.S. influence (red). The strategies are ordered from left to right by the median "increase in influence" score. The boxes extend to one quartile from the median, the whiskers extend 1.5 times the interquartile range, and dots show every participants response.

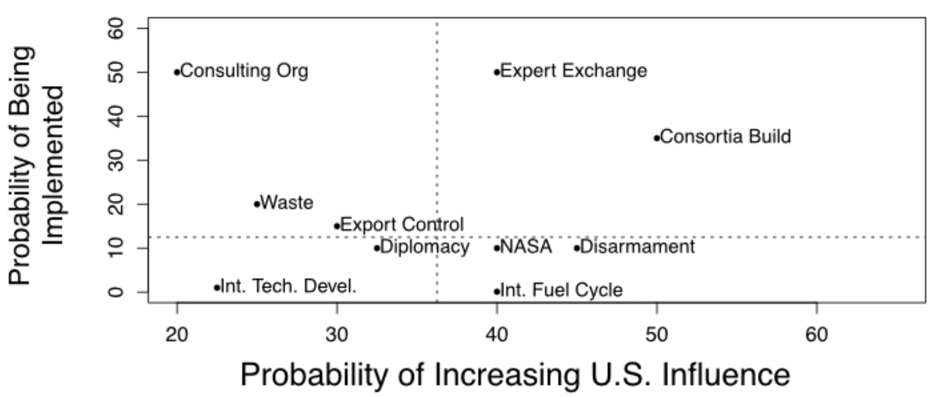

Figure A-7: Categorization of strategies based on expert evaluation of efficacy and feasibility of each over a 5-year time horizon. Dotted lines show the median of the expert evaluations for each metrics.

Table A.2: Full results for median assessed efficacy and feasibility over 5 and 15 year periods. The highest two strategies are colored green, and the lowest two strategies are colored red for each metric and time horizon.

Strategy	Efficacy, 5y	Efficacy, 15y	Feasibility, 5y	Feasibility, 15y
Export Control Reform	30	30	.15	.5
The NASA Model	40	50	.1	.15
Int. Fuel Cycle	40	50	0.0	0.1
Int. Reactor Develop.	23	30	0.01	0.1
Expert Exchanges	40	40	0.5	0.6
Diplomacy	33	40	0.1	0.9
Consulting Firm	20	25	0.5	0.7
Disarmament	45	55	0.1	0.4
Nuclear Waste	25	45	0.2	0.55
Consortia Build	50	55	0.35	0.55

A.7 Sub-Strategies

Strategy: Export Control Reform

Sub-Strategies Ranked Best

1. Establish fast-track authorizations for specific technologies and countries.
2. Design 123 Agreements on a case-by-case basis rather than requiring the Gold Standard.
3. Evaluate the foreign availability of restricted technologies and update control lists accordingly.
4. Allow the Secretary of Energy to delegate specific authorizations.

Sub-Strategies Ranked Worst

1. Consolidate authority for nuclear exports in to a single agency.
2. Allow exports to be authorized before bilateral agreements are in place.

Strategy: Internationalized Fuel Cycle

Sub-Strategies Ranked Best

1. Establish one or several international fuel storage parks that would be internationally funded and supervised.
2. Establish an International Fuel Exchange (IFE) that brokers all transactions for fueling civilian nuclear power reactors worldwide.

Sub-Strategies Ranked Worst 1. Establish international fuel reprocessing parks that are jointly funded and supervised.

Strategy: The NASA Model

Sub-Strategies Ranked Best

1. A commitment by a substantial number of federal facilities to enter into power purchase agreements with entrants offering new advanced reactors.
2. A pool of low-cost capital available to firms that make a credible case for developing a new reactor design.
3. Establish new more affordable funding mechanisms (e.g.cost-sharing arrangements) for NRC licensing of advanced reactors.

[None of the sub-strategies were marked as bad ideas by more than a few participants]

Workbook Number:___________________

We will collect the books at the end of the first day so we can do a quick summary to start the second day. Remember your workbook number so you can recover it tomorrow. We are not asking you to add your name. ***We will not link any responses to any individual participants.***

Evaluating Strategies to Restore U.S. Leadership in the International Nuclear Market and Control Regimes

September 26 and 27, 2018

Revelle Conference Room
American Association for the Advancement of Science
1200 New York Ave NW, Washington, DC 20005

Support for this event has been provided by Carnegie Mellon's Wilton E. Scott Institute for Energy Innovation (https://www.cmu.edu/energy/), a grant from The John D. and Catherine T. MacArthur Foundation for PhD student support (18-1802-152868), The Center for Climate and Energy Decision Making at Carnegie Mellon University (supported by the U.S. National Science Foundation under cooperative agreement SES-1463492; http://cedmcenter.org), the Carnegie Mellon Electricity Industry Center (http://www.cmu.edu/electricity), and academic funds from Carnegie Mellon University.

Thank you for agreeing to participate in this workshop.

This workbook contains the response sheets for the various assessment exercises that we will ask participants to complete over the course of this event. We ask you to draw upon your personal expertise and judgment as individual experts. In other words, we are not asking you to represent any organization with which you are affiliated.

This book lays out a number of specific issues that will be addressed over the course of the workshop. It also contains pages for you to express your anonymous views about those issues. The Carnegie Mellon Institutional Review Board has ruled that if you choose to complete any responses in this workbook that will make you a "human subject" as defined in 45CFR46 and that you will need to complete a consent form. If you choose not to do that, you should not provide any responses in the workbook.

We will be collecting this workbook at the end of the first day to prepare a preliminary summary of responses so that we can display and then discuss the results at the beginning of the second day.

This workshop is being held under a **modified version of the Chatham House rule**, by which we mean that in reporting on this event, you are free to say who was in the room but you **should not attribute** any of the content of the discussions and the assessments made by participants without their explicit permission. In preparing a summary of the meeting we will abide by the same rules.

Once the information from the two days has been further synthesized and we have prepared a paper summarizing what we have learned, we will share a draft with all participants before making it publicly available.

Workshop Agenda

Day 1: Wednesday, September 26, 2018

Background information.

10:00 – 10:15	Welcome and 3 to 5 sentence introductions around the table.	G. Morgan
10:15 – 10:20	Motivation for the workshop.	G. Morgan
10:20 – 10:35	Summary of the current state of the U.S. civilian nuclear enterprise.	M. Ford
10:35 – 10:50	Summary of the current state of the civilian nuclear enterprise elsewhere in the world.	A. Abdulla
10:50 – 11:05	Overview of the current international nuclear control regime.	J. Lovering
11:05 – 11:20	Discussion.	

Introduction to policy options and discussion of our assumptions.

11:20 – 11:30	Introduction to policy options that address the adverse impacts of eroding U.S. leadership in civilian nuclear power on global nuclear safety and security standards.	G. Morgan
11:30 – 11:40	Description of the assumptions that undergird our premise and are likely to influence later discussions.	A. Abdulla
11:40 – 12:00	Comments and discussion.	
12:00 – 12:30	Individual assessment of the assumptions using workbook pages 7 to 12.	
12:30 – 13:15	Lunch outside the meeting room.	

Elaboration and evaluation of candidate strategies.

13:15 – 13:40	Presentation, discussion and individual evaluations of **<u>Strategy 1:</u>** Modernize, reform and update frequently U.S. export control so as enhance U.S. competitiveness. Individual assessment on workbook pages 13 to 19.
13:40 – 14:05	Presentation, discussion and individual evaluations of **<u>Strategy 2:</u>** Develop and fund a program of international exchanges on civilian nuclear power technologies with leading nuclear nations and rising nuclear states. Individual assessment on workbook pages 20 to 26.
14:05 – 14:30	Presentation, discussion and individual evaluations of **<u>Strategy 3:</u>** Internationalize and centralize the front and back ends of the nuclear fuel cycle. Individual assessment on workbook pages 27 to 33.
14:30 – 14:55	Presentation, discussion and individual evaluations of **<u>Strategy 4:</u>** Create and fund an international development center for advanced civilian nuclear energy technologies. Individual assessment on workbook pages 34 to 39.
14:55 – 15:20	Presentation, discussion and individual evaluations of **<u>Strategy 5:</u>** Move much of civilian nuclear development out of the DOE National Labs into the private sector (like NASA did with space launch) and have the labs focus on developing and managing the nation's test facilities and performing basic technology-focused research. Individual assessment on workbook pages 40 to 47.
15:20 – 15:45	Presentation, discussion and individual evaluations of **<u>Strategy 6:</u>** Devote Primary Attention to Enhancing U.S. Diplomacy and Soft Power with the Goal of Maintaining Strong International Nuclear Security Norms. Individual assessment on workbook pages 48 to 52.
15:45 – 16:00	Break for coffee, tea and juice
16:00 – 16:45	General discussion. Possible development of one or two additional strategies.
16:45 – 17:15	Individual evaluations of other strategies proposed by workshop participants on workbook pages 53 to 58.
18:30 –	Reception and Dinner at Henley Park Hotel.

Day 2: Thursday, September 27, 2018

08:30 – 09:00	Breakfast outside the meeting room.	

Summary of Results from Day 1.

09:00 – 09:20	Summary of workbook results from Day 1.	J. Lovering
09:20 – 09:40	Discussion.	

Discussion and Evaluation of Feasibility and Priorities.

09:40 – 10:00	Discussion of domestic and international political feasibility and consideration of importance.	A. Abdulla
10:00 – 10:30	Individual assessment of the political feasibility and importance of each of the various strategies on workbook pages 60 to 64.	
10:30 – 10:45	Break for coffee, tea and juice.	
10:45 – 11:00	Discussion: If we are going to continue to work on this issue, what should we be doing? If, in addition to commenting, you want to write a note about this, please use workbook pages 65 to 67.	G. Morgan

Meeting Wrap Up.

11:00 – 12:00	Go around the table and solicit final comments from each individual participant. If, in addition to commenting you also you want to write a note about this, please use workbook pages 65 to 67.	G. Morgan
12:00 –	End – light lunch available outside the meeting room.	

Each of the sections that follow are for you to provide individual responses after we hold group discussions.

In reporting your responses, we will ***not*** link any individual responses to any individual participants.

Introduction to policy options and discussion of our assumptions.

11:30 – 11:40	Description of the assumptions that undergird our premise and are likely to influence later discussions.
11:40 – 12:00	Comments and discussion.
12:00 – 12:30	Individual assessment of the assumptions using workbook pages 6 to 12.

The premise of this workshop, and the assumptions we will be making over the next two days, are worth identifying explicitly and evaluating in greater detail. We would like to elicit your judgment on each of these below.

Q1 | Do you believe that there has in fact been a loss of U.S. influence on nuclear matters, specifically on setting global nuclear safety and security standards?

For this and subsequent questions please use the bar to provide your assessment. You can either mark an **X** on the bar or indicate a range **|-----|**.

Yes, **there has been a significant loss** of U.S. influence over matters of international nuclear safety and security	No, **there has not been any loss** of U.S. influence over matters of international nuclear safety and security

Summary questions like this always leave out important nuance. Please tell us about additional factors that you see as important and relevant that this morning's discussion did not touch on, gave too little attention, or deserve to be reinforced:

Q2 The idea of "loss of status" or "loss of influence" vis-à-vis the international control regimes may seem somewhat nebulous. Do you have any thoughts on how to operationalize this concept so that the arguments made might be more empirically grounded? What metrics or strategies would you suggest?

Comments:

Q3 Having spent the morning discussing the adverse impacts of eroding U.S. leadership in nuclear matters on global nuclear safety and security standards, we'd like your assessment of the extent to which you consider this to be a problem.

Loss of U.S. influence is **not a big deal**. The world will do just fine on nuclear safety and security if U.S. influence wanes	Loss of U.S. influence is **a very big deal**. Nuclear safety and security standards are likely to weaken considerably

Comments:

Q4 One of our premises is that over the past half century U.S. influence on the international nuclear control regime has generally been positive and constructive. To what extent do you agree?

The U.S. has generally been exercising a **malign or counterproductive** influence on international nuclear safety and security in the atomic age	The U.S. has generally been exercising a **positive or constructive** influence on international nuclear safety and nuclear security in the atomic age

Comments:

Q5 Another of our premises is that, while perhaps not essential, a vigorous civilian nuclear power industry and export market dramatically increases a country's ability to exercise meaningful influence on the international nuclear control regime. To what extent do you agree?

A vigorous civilian nuclear power industry is **a prerequisite** for a country to wield influence in international nuclear safety and security circles

A vigorous civilian nuclear power industry is **not a prerequisite** for a country to wield influence in international nuclear safety and security circles

Comments:

Q6 Some analysts have suggested that the size of the U.S. nuclear weapons stockpile and the large amount of resources spent on it and on the nuclear navy will guarantee the U.S. a large and enduring influence over the international nuclear control regime. To what extent do you agree?

U.S. nuclear weapons and nuclear propulsion in the navy will **guarantee** it having great influence over international nuclear safety and security

U.S. nuclear weapons and nuclear propulsion in the navy fall in a different domain and provide **no guarantee** of enduring influence over international nuclear safety and security

Comments:

Q7 We consider nuclear security to be a tier-one concern and its erosion an existential threat to the natural world and humanity. Large resources ought to be spent on enhancing it. To what extent do you agree with this premise?

You **greatly exaggerate** the scope of the threat (and hence the need for the U.S. to play a constructive role).

The scope of **the threat is alarming** (and hence the U.S. needs to find some way to reinvigorate efforts to enhance nuclear security).

Comments:

Elaboration and evaluation of candidate strategies.

13:15 – 13:40	Presentation, discussion and individual evaluations of **Strategy 1:** Modernize, reform and update frequently U.S. export control so as to enhance U.S. competitiveness. Individual assessment on workbook pages 13 to 19.

Proposal: Undertake a radical overhaul of the U.S. export control regime as it relates to technologies relevant to civilian nuclear power. This overhaul would:

1) Consolidate authority for nuclear exports into a single agency.
2) Allow bulk export licenses to be approved for certified exporters.
3) Evaluate the foreign availability of restricted technologies and update control lists accordingly.
4) Allow the Secretary of Energy to delegate specific authorizations.
5) Establish fast-track authorizations for specific technologies and countries.
6) Allow exports to be authorized before bilateral agreements are in place.
7) Allow government-to-government assurances to proceed in parallel with specific authorization processes.
8) Design 123 Agreements on a case-by-case basis rather than requiring the Gold Standard.
9) Make the Part 810 technology list more specific and consistent with Nuclear Supplier Group (NSG) lists.
10) Place sunset provisions on technologies added to control lists.
11) Invest more resources in determining foreign availability of technologies.
12) Set explicit time limits on approval and authorization process.
13) Allow the Department of Energy to set its own rules on deemed exports rather than rely on those of the Department of Commerce.

Rationale:

As more countries look to start their first construction of commercial nuclear plants, enhancing the competitiveness of bids made by U.S. companies could offer an opportunity to gain influence in these countries. Many have argued that the U.S. nuclear export controls are outdated and were designed for a world that no longer exists: not only was their overriding concern to prevent the Soviet Union from gaining access to U.S. technology, but the U.S. was the dominant global supplier of nuclear (and other advanced) technologies.

As countries of strategic diplomatic interest—such as Saudi Arabia—pursue nuclear power, the U.S. should perhaps become more proactive in developing nuclear partnerships and establishing trade connections that help engender in these nations America's visions of nuclear safety and nuclear security.

Challenges:

Companies are often reticent to support export control reform since, in the past, "reforms" to export control have generally made the rules stricter, not looser.

The lack of industrial or trade policy in the U.S. is a hurdle to developing technology-specific or country-specific rules. Perhaps the best example is China. Although China is a huge market for U.S. firms, there are significant concerns across industries with regard to intellectual property theft. Some countries' mingling of civilian and military nuclear technology poses a particular obstacle. Once again, China is an example of this phenomenon.

While some have made the argument that restrictions should be looser on nations that already have robust nuclear capability across the board, such as China, others have made the counterargument that the U.S. should jealously guard its competitive advantage for precisely that reason. There is also the concern about the possibility that technology may be reexported to states such as Pakistan.

Background

The Atomic Energy Act of 1954 encouraged sharing and dispersion of nuclear power technologies in exchange for commitments to forgo nuclear weapons. Most countries require a bilateral agreement between the suppler and receiving countries before nuclear exports can take place, but the US is the only country that requires such an agreement as a precursor to any export authorizations. Also, since the U.S. can import nuclear material and technology without a 123 Agreement, but cannot export without one, this arguably creates a trade imbalance.

After India's first nuclear test in 1974, the nuclear industry realized that civilian nuclear technologies that could be used in weapons program were not being properly controlled. A group of countries met in London the following year in what would become the multilateral export control organization, the Nuclear Suppliers Group (NSG). Their main task was to create a harmonized list of restricted items that could only be exported to countries that met IAEA safeguards.

One of the major disagreements on the international stage was who should be allowed to have enrichment and reprocessing technologies. The U.S. commissioned the International Nuclear Fuel Cycle Evaluation (INFCE) in 1977, which sought to evaluate the proliferation risks of various fuel cycles. However, many countries saw the U.S. opposition to reprocessing as a way to force their dependence on Western fuel services and violate their sovereign rights under the NPT to pursue peaceful uses of nuclear power.

The strict U.S. control of nuclear technology in the 1960s and 70s, particularly fuel cycle technology, was effective in the short-term in dissuading countries from domestic enrichment. However, this strategy pushed countries to look to non-US suppliers or develop domestic capabilities in the long term. With the diversity of nuclear suppliers available on the global market today, importing countries have their pick for nuclear vendors and the overly strict U.S. export controls put the country at a disadvantage. For example, Brazil chose a West German reactor over a Westinghouse package in in the 1970s because the Germans offered support for enrichment and reprocessing facilities.

Of the major nuclear vendor countries, there was significant variance in how governments thought about nuclear exports. French interest in nuclear was purely economic; they would often underbid on nuclear projects hoping to secure contracts for fuel and reprocessing services. The UK and Canada pursued exports to prop up their small domestic market yet were both ultimately hit by poor operational performance at home. The CANDU reactor was attractive to emerging nuclear countries, as it did not require enrichment (and could also be used to make weapons-grade material). However, the main country to use nuclear exports to secure diplomatic relations has always been Russia (formerly the Soviet Union). Their packages of financing and fuel services have long proven attractive to newcomer nuclear countries, and their lack of qualms about exporting to corrupt and unstable governments has also helped.

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If **only Strategy 1** were implemented, and all other U.S. public and private activities remained unchanged, what if any would be the impact on the ability of the U.S. to influence developments in international nuclear safety and security?

Five years after implementation:

Continued **decline** in U.S. influence	**No change** in U.S. influence	**Increase** in U.S. influence
◯	◯	◯

Please allocate 100 points

Fifteen years after implementation:

Continued **decline** in U.S. influence	**No change** in U.S. influence	**Increase** in U.S. influence
◯	◯	◯

Please allocate 100 points

As part of **Strategy 1** we listed 13 specific changes. In the **left-hand column**, please rank the 3 changes that would be most useful or important (1 = most useful, 2,3, and further if you want). Optionally, in the **right-hand column**, please rank which of the changes are particularly bad ideas, by which we mean that they will have very bad consequences, (1 = worst, 2,3, and further if you want).

Most useful 1, 2, 3, …	**Component of Strategy 1**	**Bad ideas 1, 2, 3, …**
	Consolidate authority for nuclear exports into a single agency.	
	Allow bulk export licenses to be approved for certified exporters.	
	Evaluate the foreign availability of restricted technologies and update control lists accordingly.	
	Allow the Secretary of Energy to delegate specific authorizations.	
	Establish fast-track authorizations for specific technologies and countries.	
	Allow exports to be authorized before bilateral agreements are in place.	
	Allow government-to-government assurances to proceed in parallel with specific authorization processes.	
	Design 123 Agreements on a case-by-case basis rather than requiring the Gold Standard.	
	Make the Part 810 technology list more specific and consistent with Nuclear Suppliers Group lists.	
	Place sunset provisions on technologies added to control lists.	
	Invest more resources in determining foreign availability of technologies.	
	Set explicit time limits on approval and authorization process.	
	Allow the Department of Energy to set its own rules on deemed exports rather than rely on those of the Department of Commerce.	

What (if any) do you see as the risks of adopting a program of the sort outlined in **Strategy 1**?

What (if any) do you see as the benefits of adopting a program of the sort outlined in **Strategy 1**?

Independent of your assessment of its efficacy, if the U.S. choose to adopt **Strategy 1**, what (if any) modifications or elaborations would you want to see made in the design of **Strategy 1** before it was adopted? Why?

13:40 – 14:05	Presentation, discussion and individual evaluations of **Strategy 2:** Develop and Fund a Program of International Exchanges on Civilian Nuclear Power Technologies with Leading Nuclear Nations and Rising Nuclear States Individual assessment on workbook pages 20 to 26.

Proposal: The U.S. Government should create and fund a program of international exchange fellows in civilian nuclear power, half of whom would be U.S. nationals who spend time abroad in facilities in states with major civilian nuclear programs and half of whom would be foreign nationals from major nuclear states who spend time in U.S. civilian nuclear facilities (national labs, corporations, the NRC, etc.). Fellowships would be open to applicants who hold a PhD or equivalent, and could be for durations of either 1 or 2 years. Participating states would at a minimum include China, France, Russia, South Korea, and the United States.

How would this help?

There is some evidence that person-to-person ties among experts can, in the long run, facilitate international collaboration and the development of international norms and formal agreements. Past example include the Pugwash, the IGY, the long saga of U.S.-Soviet interactions (chronicled by Hecker), IIASA, the Fulbright Program, and a number of others. The idea would be to strengthen existing ties and build a stronger international community: doing this via "Track 2" may in the longer run help facilitate more serious attention to the international management of fuel cycles and counter proliferation via "Track 1."

Compared with several of the other strategies outlined, this strategy would be relatively inexpensive (e.g. $1.5*60*\$300k \approx \$30x10^6/yr$).

Challenges

In the U.S., there would be a need to address IP, export control and visa issues, as well as issues of placing foreign nationals in some facilities. All of these have been successfully addressed in specific situations in the past and could in principle be solved again.

Internationally, there would be issues placing U.S. nationals in some sensitive facilities.

Background

There is rather wide agreement that Track 2 activities have played a role in laying the groundwork for a number of past achievements in arms control, the international control of nuclear materials and the development and support of regimes to limit weapons proliferation.

In the overview of Volume 1 of *Doomed to Cooperate* (excerpts from which are included in the book of background readings for this workshop), Siegfried Hecker outlines the process by which American and Russian nuclear scientists and engineers provided a "window" into each other's hearts, and led them to wonder "if they were really much more alike than different and if our common scientific roots and responsibilities for the world's most destructive weapons transcended the different political systems for which we provided the technical means for out governments' nuclear deterrents." In this two-volume set Hecker and his co-authors discuss the operation of inter-lab exchanges at length, and the resulting growth in mutual confidence and joint contributions to threat reduction, stockpile stewardship, and related activities – including, as he puts it, an effort to also "cooperate to do good, not just prevent" harm.

Writing more than four decades earlier in 1972 in his book *A History of the Pugwash Conferences*, Prof. Joseph Rotblat noted that:

> *… achievement is often a matter of judgment rather than of fact. In the highly complex problems discussed in Pugwash, where so many diverse factors interact, it is impossible to measure the influence exerted by any single factor… [After noting that he is too close to the process to assess impacts he writes that other have] … express[ed] opinions about our achievements. Thus a very senior American scientist has stated that Pugwash has been an important force in bringing better understanding between East and West in the last decade. U Thant spoke about the careful attention given to Pugwash resolutions at the United Nations and about their influence on decision-making processes by national governments. Some people go further and attribute to Pugwash the few successes achieved so far in disarmament, such as the partial test ban treaty or the non-proliferation treaty.*

In his book *Unarmned Foces, The Transnational Movement to End the Cold War*, Matthew Evangelista argues that, that while in other contexts Pugwash had important and constructive impact, in the specific context of the test ban of the late 1950s, Pugwash "seems to have played a relatively insignificant role," but that "one should not underestimate the importance of the transnational scientists' efforts" on the governments of both the U.S. and U.S.S.R. He argues that the smaller meetings and the groups that evolved out of Pugwash …proved especially valuable in promoting mutual understanding and restraint between the nuclear superpowers. Evangelista makes similar arguments about the role of the smaller

SADs group and personal diplomacy, as compared to Pugwash, a decade later, and suggests that such contacts grew in importance in the late 1980s.

The U.S. National Academies have often played a role in Track 2 activities. In his book *Scientists, Engineers, and Track Two Diplomacy*, Glenn Schweitzer documents more than 50 years of cooperative activities between the U.S. National Academies and the Soviet Academy of Sciences (ASUSSR), and more recently the Russian Academy of Sciences (RAS). He argues that these interactions have been "a major factor in encouraging and facilitating direct cooperation between hundreds of laboratories and thousands of specialists in both Russia and the United States..." and he notes that "The academies have provided advice to their respective governments, both in reports and in face-to-face meetings with government leaders, and they have often influenced government officials to look favorably at the advantages of scientific engagement over scientific confrontation." He observes that:

> *Over the years, a characteristic of many of the most notable interacademy projects has been that they were "ahead of the curve." They explored topics that were of great interest to both governments but that had not benefited from scrutiny by highly qualified, independent experts; they were held in locations not accustomed to receiving foreign visitors; or they involved organizations and individuals who were not regular participants in cooperative programs and who brought fresh perspectives to efforts to address seemingly intractable problems. In the wake of some projects [he gives examples in national security], the governments became interested in sponsoring their own programs in these areas.*

Schwitzer explains that:

> *For decades both governments have considered the track two efforts of scientific organizations to be important channels for gathering information that is openly available for the asking, for communication between intellectuals, for gaining insights into what works and what does not work in Russia, and for setting the stage for governmental programs. In a few sensitive areas, the governments maintain a tight leash on scientific interactions, but most of the early fears of the governments that exchanges would be routinely distorted for intelligence or propaganda purposes have disappeared.*

Beyond focused Track 2 activities, there are other more general examples of the benefits of personal contacts such as IIASA, Fulbright, and foreign nationals studying in U.S. universities. Whatever one thinks of the Iranian nuclear agreement, it is probably the case that the shared MIT backgrounds of Ernest Moniz and Ali Akbar Salehi helped to facilitate their interactions.

In his assessment of the Fulbright program, Leonard Sussman argues that "as the military/strategic component of American foreign relations is reduced, cultural interactions with other peoples, especially in formerly closed societies" provides an important vehicle. He cites a variety of benefits and improvements in understanding that have resulted from the two-way flow of scholars supported by the Fulbright program. He observes that:

> *The reciprocal exchange of ideas across national borders can lead to greater security and human progress. Toward this end, the principal focus of the Fulbright program has been, and should be, the enhancement of the individual intellect… the prime focus remains the intellectual empowerment of individuals, foreign and American… All learn. All teach. "Exchange" is the operative word because the process is two-way. That double flow on such a scale-more than 180,000 high-quality travelers over 45 years-is unique in history. Most valuable, this select group tests its own values and scholarship aboard. It also maintains contact with former host scholars and institutions, and so contributes-jointly-to new discovery. The exchange and its values continue for lifetimes.*

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If **only Strategy 2** were implemented, and all other U.S. public and private activities remained unchanged, what if any would be the impact on the ability of the U.S. to influence developments in international nuclear safety and security?

Five years after implementation:

Continued **decline** in U.S. influence	**No change** in U.S. influence	**Increase** in U.S. influence

Please allocate 100 points

Fifteen years after implementation:

Continued **decline** in U.S. influence	**No change** in U.S. influence	**Increase** in U.S. influence

Please allocate 100 points

What (if any) do you see as the risks of adopting a program of the sort outlined in **Strategy 2**?

What (if any) do you see as the benefits of adopting a program of the sort outlined in **Strategy 2**?

Independent of your assessment of its efficacy, if the U.S. choose to adopt **Strategy 2**, what (if any) modifications or elaborations would you want to see made in the design of **Strategy 2** before it was adopted? Why?

14:05 – 14:30	Presentation, discussion and individual evaluations of **Strategy 3:** Internationalize and Centralize the Front and Back Ends of the Nuclear Fuel Cycle Individual assessment on workbook pages 27 to 33.

Proposal: Implement a strategy to internationalize the front and back ends of the civilian nuclear fuel cycle, with the ultimate, expressed goal being the consolidation of all fresh and spent fuel in centralized, internationally supervised facilities. This strategy would:

1) Establish an International Fuel Exchange (IFE) that brokers *all* transactions for fueling civilian nuclear power reactors worldwide. Existing fuel suppliers would have to become members of the IFE.
2) Insist on the best available fuel tagging practices as well as data sharing as a price of admission into the IFE. While payments associated with such transactions could be confidential, all data on quantities and material composition would be shared with the IFE.
3) Build a central and comprehensive data repository of fabricated fuel transactions, including source, quantity, recipient, and ultimate fate.
4) Establish international fuel reprocessing parks that are jointly funded and supervised. These would help conduct reprocessing R&D and help reduce global spent fuel volumes.
5) Establish one or several international fuel storage parks that would be internationally funded and supervised. These parks would prepare spent fuel for final disposal and conduct storage R&D, though the geologic disposal repositories might not be located on those premises.
6) Establish an IAEA database of international nuclear exports to track nuclear suppliers and nuclear customers.

Under this strategy the U.S. would exercise its diplomatic influence to introduce these measures while working with the international community to mitigate any potential risks.

Rationale:

At the dawn of the atomic age, proposals were made to internationalize different elements of the nuclear fuel cycle. In 1946, the State Department released a *Report on the International Control of Atomic Energy*, which became known as the *Acheson-Lilienthal Report.* The report, written by Robert Oppenheimer, "called for the creation of the Atomic Development Authority to oversee the mining and use of fissile materials, the operation of all nuclear facilities that could produce weaponry, and the right to dispense licenses to those countries wishing to pursue peaceful nuclear research. The plan relied on Soviet-American cooperation, since its authors recognized that the Soviet Union was unlikely to cede its veto power in the United Nations Security Council over any matter. Moreover, it made no mention of when the United States should destroy its nuclear arsenal, though it did acknowledge that doing so was a necessity."[1] This acknowledgment is now a binding legal obligation, thanks to Article VI of the Nuclear Nonproliferation Treaty, which states that "each of the Parties to the Treaty undertakes to pursue negotiations in good faith on effective measures relating to cessation of the nuclear arms race at an early date and to nuclear disarmament, and on a treaty on general and complete disarmament under strict and effective international control."[(2)]

The *Acheson-Lilienthal* plan birthed a modified *Baruch Plan* that was put to a UN Atomic Energy Commission vote. "Under the Baruch Plan the Atomic Development Authority would oversee the development and use of atomic energy, manage any nuclear installation with the ability to produce nuclear weapons, and inspect any nuclear facility conducting research for peaceful purposes. The plan also prohibited the illegal possession of an atomic bomb, the seizure of facilities administered by the Atomic Development Authority, and punished violators who interfered with inspections. The Atomic Development Authority would answer only to the Security Council, which was charged with punishing those nations that violated the terms of the plan by imposing sanctions. Most importantly, the Baruch Plan would have stripped all members of the UN Security Council of their veto power concerning the issue of UN sanctions against nations that engaged in prohibited activities. Once the plan was fully implemented, the U.S. was to begin the process of destroying its nuclear arsenal." [(1)] The USSR rejected this plan.

Challenges:

The challenges to international control are obvious. A measure of national sovereignty would have to be sacrificed for the benefit of international security. (It is worth noting that this happens every time the UN Security Council adopts a resolution.) The growth of reactionary and nationalistic tendencies worldwide mean that any such proposals would either be dismissed as incredible or face an uphill battle. Forcing large industrialized nations, especially ones that have framed their nuclear ambitions as an instrument of national liberation like India, to give up unilateral control of parts of the nuclear fuel cycle might prove especially difficult. Moreover, while the U.S. has often been willing to impose restrictions on others, it has often been unwilling to sign up for restrictions on itself.

Siting new facilities might prove difficult. That said, while developing an IFE could involve physical facilities (including for fuel production and waste processing) it would not need to. Rather it could operate as a clearing house. It would however have to have some inspection and enforcement capabilities.

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If **only Strategy 3** were implemented, and all other U.S. public and private activities remained unchanged, what if any would be the impact on the ability of the U.S. to influence developments in international nuclear safety and security?

Five years after implementation:

Continued **decline** in U.S. influence	**No change** in U.S. influence	**Increase** in U.S. influence

Please allocate 100 points

Fifteen years after implementation:

Continued **decline** in U.S. influence	**No change** in U.S. influence	**Increase** in U.S. influence

Please allocate 100 points

As part of **Strategy 3** we listed 6 specific strategies. In the **left-hand column**, please rank the 3 changes that would be most useful or important (1 = most useful, 2,3, and further if you want). Optionally, in the **right-hand column**, please rank which of the changes are particularly bad ideas, by which we mean that they will have very bad consequences, (1 = worst, 2,3, and further if you want).

Most useful 1, 2, 3, …	**Component of Strategy 3**	**Bad ideas 1, 2, 3, …**
	Establish an International Fuel Exchange (IFE) that brokers *all* transactions for fueling civilian nuclear power reactors worldwide. Existing fuel suppliers would have to become members of the IFE.	
	Insist on the best available fuel tagging practices as well as data sharing as a price of admission into the IFE. While payments associated with such transactions could be confidential, all data on quantities and material composition would be shared with the IFE.	
	Build a central and comprehensive data repository of fabricated fuel transactions, including source, quantity, recipient, and ultimate fate.	
	Establish international fuel reprocessing parks that are jointly funded and supervised. These would help conduct reprocessing R&D and help reduce global spent fuel volumes.	
	Establish one or several international fuel storage parks that would be internationally funded and supervised. These parks would prepare spent fuel for final disposal and conduct storage R&D, though the geologic disposal repositories might not be located on those premises.	
	Establish an IAEA database of international nuclear exports to track nuclear suppliers and nuclear customers.	

What (if any) do you see as the risks of adopting a program of the sort outlined in **Strategy 3**?

What (if any) do you see as the benefits of adopting a program of the sort outlined in **Strategy 3**?

Independent of your assessment of its efficacy, if the U.S. choose to adopt **Strategy 3**, what (if any) modifications or elaborations would you want to see made in the design of **Strategy 3** before it was adopted? Why?

14:30 – 14:55	Presentation, discussion and individual evaluations of **Strategy 4:** Create and Fund an International Development Center for Advanced Civilian Nuclear Energy Technologies Individual assessment on workbook pages 34 to 39.

Proposal: Building on models of pre-competitive technical collaboration such as SEMATECH, the U.S. should take the lead in creating an international development and demonstration Center for Advanced Civilian Nuclear Energy Technologies (CACNET) and pledge initial support of ~$400-millon/year, contingent on U.S. support being matched by other nuclear-capable states within some reasonably short period (e.g. 5 years). For calibration the operating budget of CERN is ~$1 billion/year of which electricity is about $24 million/year.

While it would be desirable to have a physical facility located in some reasonably neutral place, rather than replicate expensive test facilities (such as high flux reactors), some of the experimental work would best be conducted in existing national facilities.

Rationale:

In addition to building on existing research coordination groups such as the Generation IV International Forum and the International Framework for Nuclear Energy Cooperation, the U.S. could seek to enhance its influence by leading a global effort to construct physical testing and demonstration facilities with international partners.

By involving the U.S. in extensive international collaboration in the development and demonstration of pre-competitive advanced civilian nuclear technologies, CACNET would help to reestablish U.S. standing in this field. That should in turn raise the level of U.S. standing and influence with respect to international regimes governing fuel cycles and proliferation.

Discussion and Challenges:

Within the U.S. there have been a variety of cooperative technology research and development organizations, examples of which include SEMATECH, America Makes, SunShot, and the National Alliance for Advanced Transportation Battery Cell Manufacture. Among these, SEMATECH is frequently held up as particularly successful (Khan et al, 2017; Hof, 2011; Grindley et al, 1994).

EU member states, as well as the EU as a whole, have also had experience in developing such programs. Examples include the Stuttgart Institute for Microelectronics (Hofflinger, 1989) and Biofuels FlightPath. There are of course also trans-national corporations, some of which like Airbus involve substantial government involvement.

Organizations like SEMATECH have been most successful when they have remained focused on pre-competitive technology development. The same would presumably be true for CACNET which like ITER would focus on technology validation and prototyping, since the closer one gets to the development of commercial products, the more difficult collaborations among competing firms and/or nations is likely to become.

The international space station (ISS) is the largest joint technology development project among nation states. It has been an undertaking by the national space agencies and programs of the U.S., EU,[1] Canada, Japan, and Russia. Brazil (Embraer) was briefly involved through an agreement with the U.S. but left the program in 2007. However, China has not been included (Kluger, 2015) and is now engaged in developing its own large and very active space program (Williams, 2018; Jones, 2018). With respect to the ISS, a Wikipedia entry[2] explains that:

"In 2007, Chinese vice-minister of science and technology Li Xueyong said that China would like to participate in the ISS. In 2010, ESA Director-General Jean-Jacques Dordain stated his agency was ready to propose to the other 4 partners that China be invited to join the partnership, but that this needs to be a collective decision by all the current partners. While ESA is open to China's inclusion, the U.S. is against it. U.S. concerns over the transfer of technology that could be used for military purposes echo similar concerns over Russia's participation prior to its membership [these were subsequently resolved]…"

American co-operation with China in space is limited. Though efforts have been made by both sides to improve relations, in 2011 new American legislation further strengthened legal barriers to co-operation, preventing NASA co-operation with China, Chinese owned companies, and even the expenditure of funds to host Chinese visitors at NASA facilities, unless specifically authorized by new laws. At the same time, China, Europe, and Russia have a co-operative relationship in several space exploration projects. Between 2007 and 2011, the space agencies of Europe, Russia and China carried out ground-based preparations for the Mars 500 project, which is designed to complement ISS-based preparations for a manned mission to Mars.

Even if other nations could be persuaded that creating CACNET was a good idea, it is clear that, given the perspectives of the current U.S. Administration and Congress, it is very unlikely that political support for the creation of CACNET

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1 Belgium, Denmark, France, Germany, Italy, The Netherlands, Norway, Spain, Sweden, Switzerland.

2 Available at: https://en.wikipedia.org/wiki/Politics_of_the_International_Space_Station. Reference citations and hyperlinks available in the original have been removed from this edited quotation.

could be developed if it included China. The situation vis-a-vis Russia is perhaps less clear.

However, Administrations and Congressional attitudes change, sometimes quite abruptly (Baumgartner & Jones, 1993). Hence a case might be made today to further elaborate this idea so that if and when a policy window (Kingdon, 1984) opens, the necessary homework has been done to underpin the development of CACNET.

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If **only Strategy 4** were implemented, and all other U.S. public and private activities remained unchanged, what if any would be the impact on the ability of the U.S. to influence developments in international nuclear safety and security?

Five years after implementation:

Continued **decline** in U.S. influence	**No change** in U.S. influence	**Increase** in U.S. influence

Please allocate 100 points

Fifteen years after implementation:

Continued **decline** in U.S. influence	**No change** in U.S. influence	**Increase** in U.S. influence

Please allocate 100 points

What (if any) do you see as the risks of adopting a program of the sort outlined in **Strategy 4**?

What (if any) do you see as the benefits of adopting a program of the sort outlined in **Strategy 4**?

Independent of your assessment of its efficacy, if the U.S. choose to adopt **Strategy 4**, what (if any) modifications or elaborations would you want to see made in the design of **Strategy 4** before it was adopted? Why?

14:55 – 15:20	**Strategy 5:** Move much of civilian nuclear development out of the DOE National Labs into the private sector (like NASA did with space launch) and have the labs focus on developing and managing the nation's text facilities and performing basic technology-focused research. Individual assessment on workbook pages 40 to 47.

Proposal: Rather than have the DOE National Laboratories serve as the locus of national development activity for advanced civilian nuclear power, adopt a model similar to what NASA has used for space launch. Create incentives for new commercial actors to do the technical development (presumably at *much* lower cost) and refocus the efforts of the labs on providing them with shared expensive test facilities.

How would this help?

The program would accelerate commercialization of several advanced nuclear designs that could be both cost-competitive for applications in electricity generation and high temperature process heat and competitive against other nuclear vendors bidding for international projects. This might result in giving U.S. vendors an ability to sell smaller, modularly fabricated nuclear reactors and help revive the U.S. role as a leader in international nuclear trade.

Difficulties in putting such a strategy in place

There is a fundamental difference between space launch and new civilian nuclear power. There is large and growing market demand, from both government and the private sector, for affordable space launch. At the moment, there is no such market demand for advanced nuclear reactors–indeed, so long as natural gas is cheap, commercial risks of using nuclear are high, and there is no direct or indirect cost associated with emitting CO_2 to the atmosphere, there are strong incentives in the market *against* adopting new nuclear.

For this reason, if this strategy is to succeed, substantial changes will need to be made in the incentives faced by private firms. Apart from implementing serious constraints on the emission of CO_2, these include:

- A commitment by a substantial number of federal facilities to enter into power purchase agreements with entrants offering new advanced reactors.
- Substantial tax breaks and regulatory streamlining for firms that are prepared to use new advanced reactors as a source of process heat.

- A pool of low-cost capital available to firms that make a credible case for developing a new reactor design.
- Incentives (inducement prizes) for technology demonstration.
- Convert federal and state renewable energy mandates into zero or very low carbon energy standards.
- Development by DOE of a fast reactor test facility[3] and other advanced facilities that are made available at modest cost to qualified private-sector developers of advanced civilian reactors and not to NNSA or the Navy.
- Establish new, more affordable funding arrangements (e.g. cost-sharing) for NRC licensing of advanced reactors.
- Streamline the licensing process for advanced reactors.
- Increase funding for the ExIm bank and allow it to fund U.S. nuclear projects abroad.

Developing the NASA Commercial Orbital Transportation Services (COTS) program and related programs (CRS & C3PO) required significant leadership and initiative from the Bush Administration starting in 2005 and represented a major shift in how NASA operated. Clearly there could be considerably push-back from entrenched players, including national labs and their constituents. Showcasing the success of the NASA programs and their massive cost savings – along with stressing the expanded role the labs would play in developing and providing shared test facilities, could help promote the benefits of investing in this new innovation ecosystem rather than in traditional, top-down technology development. Pointing to other recent examples of this type of commercialization policy (e.g. America COMPETES and ARPA-E) could also help.

Background

All countries that developed their own nuclear reactor technology did so through centralized programs by national governments, often with state-owned or state-supported development firms and with deployment through regulated or state-owned utilities. With the recent wave of utility regulation and budget austerity, such top-down programs may now be less tenable in the U.S. In addition, some have voiced concern that top-down programs have often not developed nuclear power technologies that are attractive to markets, certainly not for today's deregulated markets.

Similar to nuclear power, space travel has typically been the sole domain of federal governments, not the private sector. Yet NASA took a dramatic pivot in 2005 when they decided to invest heavily in stimulating the nascent commercial

[3] Currently, U.S. companies must go to Russia, China, or India to test their fuels.

spaceflight industry with an eye toward contracting launch services in the future, rather than commission Boeing or Lockheed to design a new space shuttle for sole use by NASA. The program proved wildly successful, moving the U.S. from zero commercial launches to the world leader in commercial launch activity in just 7 years. NASA has now contracted with SpaceX to deliver cargo to the ISS and is planning on future contracts for crew delivery as well. NASA spent significantly less money to end with a more diversified private sector from which they could contract services and helped the US spaceflight industry get off the ground.

In a 2013 paper, Chad Anderson argues:

"The NASA versus commercial space argument is a false dichotomy; the answer lies in partnerships… These partnerships allow each party to focus on their core competencies, while leveraging the strengths of the other. The commercial space industry can build upon the existing transportation infrastructure and make it better by focusing on profits, cost-cutting, and efficiency. NASA can focus on what it is meant to do, that which pushes the boundaries of human knowledge and has common value but no clear path to profitability."

Applying this model to the civilian nuclear power industry, the private sector should focus on developing and commercializing new advanced designs, and the DOE should focus on two things: 1) providing test facilities and specialized technical support to those firms; and 2) performing basic research that is motivated in large part by meeting the needs of the next generation of private developers.

In different, but related domains, the 2010 reauthorization of the America COMPETES Act set guidelines for federal agencies to use inducement prizes to stimulate innovation in key industries. The Advanced Research Projects Agency-Energy (ARPA-E) was created under the original 2007 America COMPETES Act but received its first funding with the 2009 stimulus act. ARPA-E advances R&D in risky technologies and helps them achieve commercialization; they began their first nuclear funding opportunities in late 2017.

References

1. Anderson, C. Rethinking public–private space travel. *Space Policy*, *29*(4), 266-271. (2013)
2. Aumeier, S. & Allen, T. How to Reinvigorate US Commercial Nuclear Energy. *Issues Sci. Technol.* (2017).
3. Commercial Space Launch Act, 49 **U.S.C. §§ 2601-2623** (Supp. 1984).
4. Ichord, R. F. *US Nuclear-Power Leadership and the Chinese and Russian Challenge*. (2018).
5. Lovering, J., King, L. & Nordhaus, T. *How to make nuclear innovative: Lessons from other advanced industries*. (2017).

6. Secretary of Energy Advisory Board. *Report of the Task Force on the Future of Nuclear Power.* (2016) https://www.energy.gov/sites/prod/files/2016/10/f33/9-22-16_SEAB%20Nuclear%20Power%20TF%20Report%20and%20transmittal.pdf
7. Williams, H. Innovation Inducement Prizes: Connecting Research to Policy. *J. Policy Anal. Manag.* **00,** 1–25 (2012).

If **only Strategy 5** were implemented, and all other U.S. public and private activities remained unchanged, what if any would be the impact on the ability of the U.S. to influence developments in international nuclear safety and security?

Five years after implementation:

Continued **decline** in U.S. influence	**No change** in U.S. influence	**Increase** in U.S. influence

Please allocate 100 points

Fifteen years after implementation:

Continued **decline** in U.S. influence	**No change** in U.S. influence	**Increase** in U.S. influence

Please allocate 100 points

As part of **Strategy 5** we listed 8 specific changes. In the **left-hand column**, please rank the 3 changes that would be most useful or important (1 = most useful, 2,3, and further if you want). Optionally, in the **right-hand column**, please rank which of the changes are particularly bad ideas, by which we mean that they will have very bad consequences, (1 = worst, 2,3, and further if you want).

Most useful 1, 2, 3, …	Component of Strategy 5	Bad ideas 1, 2, 3, …
	A commitment by a substantial number of federal facilities to enter into power purchase agreements with entrants offering new advanced reactors.	
	Substantial tax breaks and regulatory streamlining for firms that are prepared to use new advanced reactors as a source of process heat.	
	A pool of low-cost capital available to firms that make a credible case for developing a new reactor design.	
	Incentives (inducement prizes) for technology demonstration.	
	Convert federal and state renewable energy mandates into zero or very low carbon energy standards.	
	D velopment by DOE of a fast reactor test facility and other advanced facilities that are made available at modest cost to qualified private-sector developers of advanced civilian reactors and not to NNSA or the Navy.	
	Establish new more affordable funding mechanisms (e.g. cost-sharing arrangements) for NRC licensing of advanced reactors.	
	Streamline the licensing process for advanced reactors.	
	Increase funding for the ExIm bank and allow it to fund U.S. nuclear projects abroad.	

What (if any) do you see as the risks of adopting a program of the sort outlined in **Strategy 5**?

What (if any) do you see as the benefits of adopting a program of the sort outlined in **Strategy 5**?

Independent of your assessment of its efficacy, if the U.S. choose to adopt **Strategy 5**, what (if any) modifications or elaborations would you want to see made in the design of **Strategy 5** before it was adopted? Why?

15:20 – 15:45	Presentation, discussion and individual evaluations of **Strategy 6:** Devote Primary Attention to Enhancing U.S. Diplomacy and Soft Power with the Goal of Maintaining Strong International Nuclear Security Norms Individual assessment on workbook pages 48 to 52.

Proposal: Rather than focus on trying to recreate a strong U.S. commercial sector in civilian nuclear energy as a strategy to maintain influence internationally, the U.S. should refocus its efforts on funding and mounting a political diplomatic effort on non-proliferation and security. This might be seen as the German model.

As the U.S. still has the world's second largest stockpile of nuclear weapons, there is little chance that we would exit the international security stage completely. However, the U.S. could recommit to international security regimes such as IAEA, and increase participation in multilateral commissions on nonproliferation. Under such a strategy the U.S. would push for strengthening of the NPT, insist on Additional Protocols, and increase diplomatic penalties for non-compliance. They could also commit more funding for IAEA inspections, and call on other countries to do the same. The U.S. could work through domestic agencies like NRC and the State Department to pursue this agenda. The U.S. would also increase the number of staff assigned to work with NSG, appoint an ambassador to the IAEA, and increase staff support their as well.

How would this help?

If the goal is to constrain nuclear weapons proliferation, relying on civilian nuclear trade is a rather oblique tool. The U.S. might be more effective if it were to focus *directly* on diplomatic efforts to strengthen safeguards and impose sanctions on non-complying countries.

The NRC already works with regulators in other countries to train their staff on safety and security oversight. Under this policy scenario these programs would be expanded. The U.S. would also increase diplomatic staff for the IAEA.

Difficulties in putting such a strategy in place

Countries like Russia and China with strong nuclear export businesses might still exert outsized influence on newcomer nuclear countries. Unless the funding mechanism for the NRC is changed, it might have reduced ability to train regulators in other countries, as their budget is predominantly fee-based (although most countries do pay for these services). The NRC might also lose reputation as it has a reduced and out-of-date workload domestically.

Some countries may consider the U.S. posture on non-proliferation hypocritical as it has made little progress in disarmament as required under Article VI of the NPT.

Background

As the inventor of atomic weapons, the U.S. has had an inherent leadership position in global nuclear security since the dawn of the atomic age. With the original Atomic Energy Act of 1946, the U.S. exerted such strict control over nuclear technology, that it would not even share information with Manhattan project collaborators, Canada and the UK most notably. But with Eisenhower's Atoms for Peace speech and the founding of the IAEA, the U.S. loosened its grip while still maintaining its leadership position.

Even as America's large stockpile of nuclear weapons has been a tool to maintain global influence, it can also act as a barrier. Notably, the push for a Non-Proliferation Treaty was led by non-nuclear weapons states. The U.S.'s continued limited progress on disarmament also erodes authority among new nuclear countries who are forced to forgo even enrichment (which is allowed under the NPT) by a country with close to 7,000 nuclear weapons that is not following Article VI of the NPT (which requires working toward disarmament).

In 2010, the Obama Administration began the Nuclear Security Summit, a series of four bi-annual international meetings focused on reducing the threat of nuclear terrorism. Most notably, the summit introduced the idea of "gift basket diplomacy", where countries brought packages of promises and policies that would increase their domestic security. Rather than reach consensus or agree to binding commitments, countries hoped to set a good example to others of what they would offer. The US played a strong leadership role in these summits.

References:

1. International Institutions and Global Governance Program. "The Global Nuclear Nonproliferation Regime." *Council for Foreign Relations.* May 21, 2012 https://www.cfr.org/report/global-nuclear-nonproliferation-regime
2. NRC. "International Policy Statement". (2014) https://www.nrc.gov/docs/ML1413/ML14132A317.pdf
3. Alger, J. & Findlay, T. Strengthening Global Nuclear Governance. *Issues Sci. Technol.* (2010).

If **only Strategy 6** were implemented, and all other U.S. public and private activities remained unchanged, what if any would be the impact on the ability of the U.S. to influence developments in international nuclear safety and security?

Five years after implementation:

Continued **decline** in U.S. influence	**No change** in U.S. influence	**Increase** in U.S. influence

Please allocate 100 points

Fifteen years after implementation:

Continued **decline** in U.S. influence	**No change** in U.S. influence	**Increase** in U.S. influence

Please allocate 100 points

What (if any) do you see as the risks of adopting a program of the sort outlined in **Strategy 6**?

What (if any) do you see as the benefits of adopting a program of the sort outlined in **Strategy 6**?

Independent of your assessment of its efficacy, if the U.S. choose to adopt **Strategy 6**, what (if any) modifications or elaborations would you want to see made in the design of **Strategy 6** before it was adopted? Why?

16:00 – 16:30	General discussion – what other discrete options should we be considering?
16:30 – 17:00	Individual evaluations of other strategies proposed by workshop participants. Pages 53 to 58.

Group Developed Strategy 7:____

If **only Strategy 7** were implemented, and all other U.S. public and private activities remained unchanged, what if any would be the impact on the ability of the U.S. to influence developments in international nuclear safety and security?

Five years after implementation:

Continued **decline** in U.S. influence	**No change** in U.S. influence	**Increase** in U.S. influence
◯	◯	◯

Please allocate 100 points

Fifteen years after implementation:

Continued **decline** in U.S. influence	**No change** in U.S. influence	**Increase** in U.S. influence
◯	◯	◯

Please allocate 100 points

What (if any) do you see as the risks of adopting a program of the sort outlined in **Strategy 7**?

What (if any) do you see as the benefits of adopting a program of the sort outlined in **Strategy 7**?

Independent of your assessment of its efficacy, if the U.S. choose to adopt **Strategy 7**, what (if any) modifications or elaborations would you want to see made in the design of **Strategy 7** before it was adopted? Why?

Group Developed **Strategy 8**:____

If **only Strategy 8** were implemented, and all other U.S. public and private activities remained unchanged, what if any would be the impact on the ability of the U.S. to influence developments in international nuclear safety and security?

Five years after implementation:

Continued **decline** in U.S. influence	**No change** in U.S. influence	**Increase** in U.S. influence

Please allocate 100 points

Fifteen years after implementation:

Continued **decline** in U.S. influence	**No change** in U.S. influence	**Increase** in U.S. influence

Please allocate 100 points

What (if any) do you see as the risks of adopting a program of the sort outlined in **Strategy 8**?

What (if any) do you see as the benefits of adopting a program of the sort outlined in **Strategy 8**?

Independent of your assessment of its efficacy, if the U.S. choose to adopt **Strategy 8**, what (if any) modifications or elaborations would you want to see made in the design of **Strategy 8** before it was adopted? Why?

Work Book Sections for Day 2

09:40 – 10:00	Discussion of domestic and international political feasibility and consideration of importance.
10:00 – 10:30	Individual assessment of the political feasibility and importance of each of the various strategies on workbook pages 59 to 64.

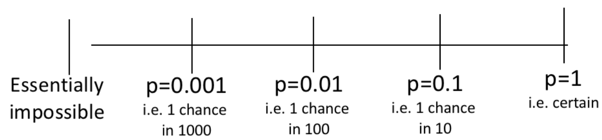
Up until now, citing Kingdon (1984) and Baumgartner & Jones (1993), we have asked you to try to ignore the feasibility of the strategies we have been considering and only assess their individual efficacy *if they could be implemented*.

Now we'd like to ask you to consider feasibility and also consider combinations of strategies.

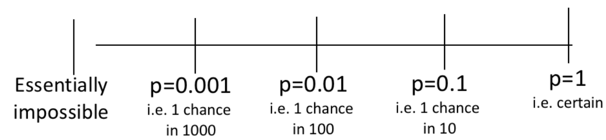
We'll start with feasibility. Please think about the ways in which the U.S. political environment might evolve over the next 5 and 15 years. For each scenario, please mark an **X** to indicate the probability that you think each strategy might be implemented assuming there are people prepared to work to make it happen.

Strategy 1: Modernize, Reform and Frequently Update U.S. Export Control to Enhance U.S. Competitiveness.

Probability you assess that a policy like this could be adopted within the next 5 years.

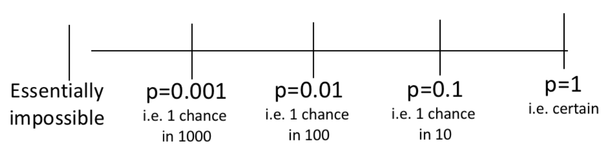


Probability you assess that a policy like this could be adopted within the next 15 years.

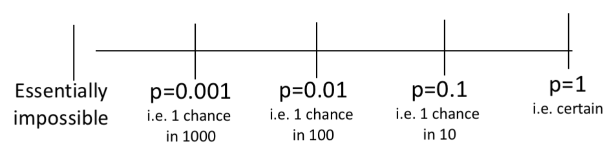


Strategy 2: Develop and Fund a Program of International Exchanges on Civilian Nuclear Power Technologies with Leading Nuclear Nations and Rising Nuclear States.

Probability you assess that a policy like this could be adopted within the next 5 years.

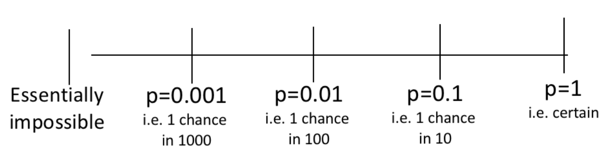


Probability you assess that a policy like this could be adopted within the next 15 years.

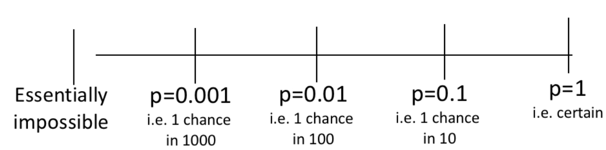


Strategy 3: Internationalize and Centralize the Front and Back Ends of the Nuclear Fuel Cycle.

Probability you assess that a policy like this could be adopted within the next 5 years.

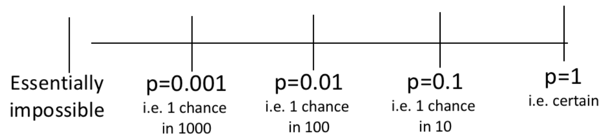


Probability you assess that a policy like this could be adopted within the next 15 years.

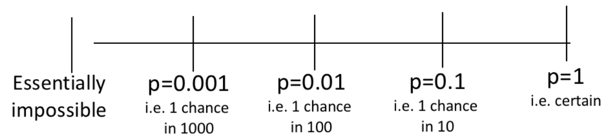


Strategy 4: Create and Fund an International Development Center for Advanced Civilian Nuclear Energy Technologies.

Probability you assess that a policy like this could be adopted within the next 5 years.

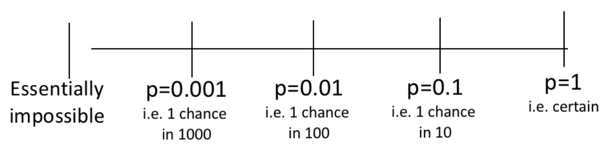


Probability you assess that a policy like this could be adopted within the next 15 years.

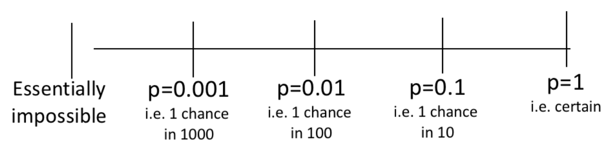


Strategy 5: Apply Increased Investment and Coherent Management across the U.S. Nuclear Innovation Ecosystem to Accelerate the Development and Commercialization of Advanced Reactors.

Probability you assess that a policy like this could be adopted within the next 5 years.

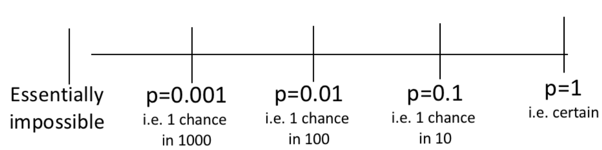


Probability you assess that a policy like this could be adopted within the next 15 years.

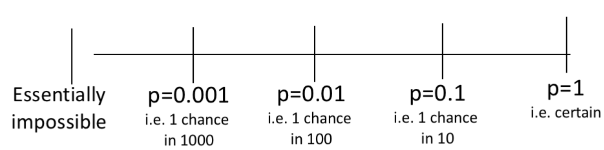


Strategy 6: Devote Primary Attention to Enhancing US Diplomacy and Soft Power with the Goal of Maintaining Strong International Nuclear Security Norms.

Probability you assess that a policy like this could be adopted within the next 5 years.



Probability you assess that a policy like this could be adopted within the next 15 years.



Strategy 7 Identified yesterday by the group: ______________________________

Probability you assess that a policy like this could be adopted within the next 5 years.

Essentially impossible	p=0.001 i.e. 1 chance in 1000	p=0.01 i.e. 1 chance in 100	p=0.1 i.e. 1 chance in 10	p=1 i.e. certain

Probability you assess that a policy like this could be adopted within the next 15 years.

Essentially impossible	p=0.001 i.e. 1 chance in 1000	p=0.01 i.e. 1 chance in 100	p=0.1 i.e. 1 chance in 10	p=1 i.e. certain

Strategy 8 Identified yesterday by the group: ______________________________

Probability you assess that a policy like this could be adopted within the next 5 years.

Essentially impossible	p=0.001 i.e. 1 chance in 1000	p=0.01 i.e. 1 chance in 100	p=0.1 i.e. 1 chance in 10	p=1 i.e. certain

Probability you assess that a policy like this could be adopted within the next 15 years.

Essentially impossible	p=0.001 i.e. 1 chance in 1000	p=0.01 i.e. 1 chance in 100	p=0.1 i.e. 1 chance in 10	p=1 i.e. certain

A number of the strategies we have been discussing are complementary and/or would work particularly well together. Please indicate which groups of policies would be most effective if one could implement two, three or four together.

Please check the box on the left for the **two** strategies that you believe would be most effective together if ***only two*** could be implemented:

☐ **Strategy 1:** Modernize, Reform and Frequently Update U.S. Export Control to Enhance U.S. Competitiveness.	Rationale for this choice of two:
☐ **Strategy 2:** Develop and Fund a Program of International Exchanges on Civilian Nuclear Power Technologies with Leading Nuclear Nations and Rising Nuclear States.	
☐ **Strategy 3:** Internationalize and Centralize the Front and Back Ends of the Nuclear Fuel Cycle.	
☐ **Strategy 4:** Create and Fund an International Development Center for Advanced Civilian Nuclear Energy Technologies.	
☐ **Strategy 5:** Apply Increased Investment and Coherent Management across the U.S. Nuclear Innovation Ecosystem to Accelerate the Development and Commercialization of Advanced Reactors.	
☐ **Strategy 6:** Devote Primary Attention to Enhancing US Diplomacy and Soft Power with the Goal of Maintaining Strong International Nuclear Security Norms.	
☐ **Strategy 7** identified by group: ______________________	
☐ **Strategy 8** identified by group: ______________________	

Please check the box for **three or four** strategies that you believe would be most effective together if only ***three or four*** could be implemented:

- ? **Strategy 1:** Modernize, Reform and Frequently Update U.S. Export Control to Enhance U.S. Competitiveness.
- ? **Strategy 2:** Develop and Fund a Program of International Exchanges on Civilian Nuclear Power Technologies with Leading Nuclear Nations and Rising Nuclear States.
- ? **Strategy 3:** Internationalize and Centralize the Front and Back Ends of the Nuclear Fuel Cycle.
- ? **Strategy 4:** Create and Fund an International Development Center for Advanced Civilian Nuclear Energy Technologies.
- ? **Strategy 6:** Devote Primary Attention to Enhancing US Diplomacy and Soft Power with the Goal of Maintaining Strong International Nuclear Security Norms.
- ? **Strategy 7** identified by group: ________________________
- ? **Strategy 8** identified by group: ________________________

Rationale for this choice of two:

These pages are for any notes you may wish to make for the final two sessions of the workshop:

10:45 – 11:00	Discussion: If we are going to continue to work on these issues, what should we be doing?
11:00 – 12:00	Go around the table and solicit final comments from each individual participant.

Appendix B

Appendices for Chapter 3

B.1 Modeling Microreactors

The Nuclear Energy Institute (2018) reviewed microreactor technology for potential Department of Defense deployment and found five main developers in the U.S. working on designs: General Atomics, NuScale, Oklo, Westinghouse, and X-Energy. These microreactor concepts are summarized in Table B.1

Table B.1: A summary of microreactor concepts farthest along in development. Reactor technology acronyms: High-Temperature Gas-Cooled Reactor (HTGR), Heat Pipe Reactor (HPR). Fuel terminology: Low-enriched Uranium (LEU) less than 5% U235, High-Assay Low-Enriched Uranium (HALEU) is enriched to 5%-20%.

Vendor	Technology	Capacity	Core Lifetime	Fuel Type & Enrichment
General Atomics	HTGR	4-10 MWe	30 years	1% U_{235} Silica Carbide
NuScale	HPR	1-10MWe	>10 years	HALEU
Oklo, Inc.	HPR	1.5MWe	<20 years	Low-enriched metal fuel
Westinghouse Evinci	HPR	0.2-15 MWe	>10 years	HALEU Oxide
X-energy	HTGR	10MWth	10 years	HALEU TRISO

Table B.2: Comparison of the two different methods for modeling nuclear reactors in HOMER.

	NPS Model	**Generator Model**
Summary	Acts like a wind turbine, where you set the hourly electrical output (100% of power rating all year for nuclear). HOMER optimizes number of units deployed.	Acts like a diesel generator, but with attributes of nuclear fuel (cost, emissions, heat rate). You specify # of units, HOMER optimizes generation for each unit separately.
Sensitivity	(Not Capital or O&M), Fuel Costs, Minimum Load Ratio, Minimum Runtime, Lifetime (operating hours)	Capital Costs, Fixed O&M, Lifetime (years), Required Operating Reserve
Output	Number of reactors. Total costs.	Annual generation profile and load factor for each 1 MW reactor. Total costs and O&M costs for each

B.2 HOMER Model Paramters

Table B.3: HOMER Model Parameters for the system, project, and included technologies.

System	**Parameters** Project Lifetime: 25 years	
Economics	Discount Rate 8% Inflation rate: 2% Real Discount Rate: 5.88%	
Diesel	Initial capital cost: $0.00 Replacement cost: $500/kW O&M cost: $0.02-0.03/hour Fuel price: $0.5-$3/liter Minimum Load Ratio: 25% Lifetime: 20,000-80,000 hours	
Nuclear	**NPS Model**	**Generator Model**
	Capacity: 1MWe	Same as NPS
	Capital Cost: $5,000-$35,000/kW	Same as NPS
	Replacement Cost: $5,000-$35,000/kW	Same as NPS
	Lifetime: 5-25 years	Lifetime: 87,600-219,000 operating hours
	O&M Cost: $88,000-$260,000/reactor-yr	Same as NPS
	Fuel Cost: $44,000-$130,000/reactor-yr	Fuel Cost: $5-$15/MWh
	Min. Operating Reserve: 0-25%	Min. Load Ratio: 0-50%
Batteries	**1 MWh Li-Ion Battery**	**1 kWh Lead-Acid Battery**
	Capital Cost: $700,000	Capital Cost: $300
	Replacement Cost: $700,000	Replacement Cost: $300
	O&M Cost: $10,000/yr	O&M Cost: $10/year
	Lifetime: 15 years	Lifetime: 10 years
	Throughput: 3 GWh	Throughput: 800kWh
	Voltage: 600V	Voltage: 12V
Renewables	**Solar PV**	**Wind Turbine**
	Capital cost: $2,500/kW	Capital Cost: $2,000/kW
	O&M: $10/year/kW	O&M: $30,000/year
	Lifetime: 25 years	Lifetime: 25 years
	Derating Factor: 80%	Hub height: 80 meters

B.3 Full Community B Results

100% Nuclear

As Community B's peak load in 2015 was 1.8MW, the result of the HOMER optimization was to build two 1MW reactors, at a net present cost of $26 million and a levelized cost of energy of $0.20/kWh. The annual load factor for the two reactors is 59%, but the resulting cost is still less than diesel alone. When renewables are added to the system, HOMER finds the lowest cost system still includes two 1MW reactors but also a single 1.5MW wind turbine, for a slightly higher net present cost, $29 million.

Nuclear & Diesel

When HOMER was allowed to optimize over both nuclear and diesel fuels, the lowest cost scenario can cover all of the load with two 1MW nuclear reactors. However, the optimal system also includes 2MWe of diesel capacity, although it never generates electricity over the course of the year. This diesel generators are likely meeting a need for redundant capacity and operating reserves. The next best system includes just one 1MW reactor and 2MW of diesel capacity, but this system actually generates a lot of electricity from diesel, at an NPC of $38M and an LCOE of $0.29/kWh.

When renewables are added to this portfolio, the result is to build only one 1MWe nuclear reactor, 2MWe of diesel capacity, and two 1.5MW wind turbines. Although this system consumes significantly more diesel and is more expensive than the pure nuclear scenario, $29 million NPC or $0.22/kWh.

Nuclear & Batteries

When batteries were added to the portfolio, HOMER optimized the system to still include two 1 MWe nuclear reactors along with a 245kWh lead-acid battery. The net present cost of this system is slightly higher than the 100% nuclear scenario, $26.4 million with an LCOE of $0.20/kWh. The batteries are likely serving to maintain a higher operating reserve on the nuclear reactors. Including renewables increases the cost further, and includes only one 1.5MW wind turbine.

100% Renewables

When optimizing over a renewables and batteries scenario, the result was again a significant over build of capacity: 5.2MW solar PV, 13.5MW wind, and 87MWh of lead-acid batteries. The net present cost was more than double the next cheapest scenario, $108 million with a levelized cost of $0.81/kWh. This system generates 76% more electricity than demand over the year, an excess 35 GWh.