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A retrospective analysis of funding and focus in US advanced fission innovation

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Abstract

Deep decarbonization of the global energy system will require large investments in energy innovation and the deployment of new technologies. While many studies have focused on the expenditure that will be needed, here we focus on how government has spent public sector resources on innovation for a key carbon-free technology: advanced nuclear. We focus on nuclear power because it has been contributing almost 20% of total US electric generation, and because the US program in this area has historically been the world's leading effort. Using extensive data acquired through the Freedom of Information Act, we reconstruct the budget history of the Department of Energy's program to develop advanced, non-light water nuclear reactors. Our analysis shows that—despite spending $2 billion since the late 1990s—no advanced design is ready for deployment. Even if the program had been well designed, it still would have been insufficient to demonstrate even *one* non-light water technology. It has violated much of the wisdom about the effective execution of innovative programs: annual funding varies fourfold, priorities are ephemeral, incumbent technologies and fuels are prized over innovation, and infrastructure spending consumes half the budget. Absent substantial changes, the possibility of US-designed advanced reactors playing a role in decarbonization by mid-century is low.

1. Introduction

Substantial scholarship has emerged around the need for radical innovation in energy technologies to reduce emissions and stabilize the climate [1, 2]. Along with recommending a large increase in public sector spending on fundamental innovation and early deployment [3–5], this work has also emphasized the need for a wide array of technologies, including nuclear power [6]. For the study of energy innovation, nuclear power is particularly interesting because it has been generating almost 20% of total US electricity for three decades, and accounts for more than half of all extremely low-carbon US electricity. Also, there is a history of efforts to invest in new designs, and that history can reveal how the public sector may need to reorganize its efforts to innovate.

Here we focus on a particular type of nuclear power—advanced, non-light water reactors. Energy planners worldwide have long envisioned a nuclear enterprise in which these designs would replace the current fleet of light water reactors (LWRs). Some of these would operate at higher temperatures, allowing reactors to provide energy services that existing reactors cannot [7]. Some could operate for decades without refueling and burn up most of their fuel, which would reduce the volume of spent nuclear fuel generated, though that waste may be of higher toxicity [8–13]. Moreover, some are theorized to be safer than LWRs, or more resistant to proliferation [8]. In the US, the Department of Energy's (DOE) Office of Nuclear Energy (NE) has embraced this transition, and its support is needed if this future is ever to materialize in the US, since it is charged with catalyzing nuclear fission innovation [14]. However, despite repeated commitments to a non-light water future [15–18] and non-trivial investments by NE, no such design is remotely ready for deployment today [19].

Once the global leader, the US pioneered several non-light water concepts in the first two decades of the

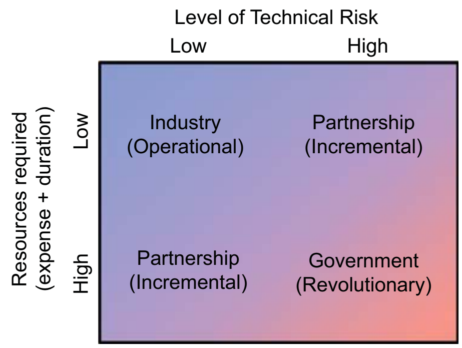

Figure 1. Classical roles of industry and government in innovation. Generally, government is expected to support fundamental R&D or potential technological breakthroughs that have high levels of technical risk or require large resources. Industry is responsible for operational innovations that sustain and optimize its revenue base [22, 23].

atomic age [10], and constructed large-scale demonstrations that operated well into the 1980s [12, 13]. High cost and disappointing performance, together with the commercial commitment to LWRs, deflated interest in advanced designs in the 1990s [13]. The nadir of support came in 1998, when NE's research activities were zeroed out, and its budgetary role was limited to facility maintenance [20]. Over the past two decades, growing concerns about climate change, the imminent retirement of a significant fraction of the current fleet of LWRs, and the limitations of LWR technology [21] have led to a resurgence of interest in non-light water reactors. As a result, NE has made new investments in a number of non-light water initiatives. Here, we investigate how effectively those resources have been allocated, and how NE has performed as a steward of nuclear technology innovation.

The efficacy of a government research and development (R&D) program is dependent on a number of technical, economic, and political factors. Markets can dictate where government attention ought to lie and which technologies ought to be prioritized. However, because markets are focused on the shorter term, technical judgment is also important in setting priorities for more fundamental R&D. Moreover, the appropriations process—including the size and stickiness of government funding priorities—depends on partisan politics, special interests, organizational inertia, and personal relationships. We acknowledge the importance of these realities in determining NE's funding levels and programmatic choices, and therefore the efficacy of its investments. Here we focus on analyzing how NE has actually spent the public sector resources allocated to its advanced innovation mission.

Our analysis examines NE's performance in the context of the classic role of government in technology innovation: support for fundamental R&D [22–25]. In this paradigm, applied R&D offices like NE fund potential breakthrough technologies at the early stages of technological readiness [23, 26]. This model is based on the assumption that industry will eschew high-risk, high-expense, or long-duration research, focusing instead on more proximate and proven activities that maximize the net present value of its existing revenue streams [27]. In figure 1, we display the roles that government and industry play in this continuum. As technical risk is retired and technological readiness increases, the innovation burden should shift to industry [28, 29]. Feedback from recent studies that look at the roles of government and industry in advanced fission innovation supports this model [30].

2. Methods

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

Once it became clear that its elimination was not going to be permanent, NE began developing a technology strategy that included DOE's twenty-first century vision for advanced reactors. Released by its Research Advisory Council in 2001, it laid out a path for deploying new reactors as a logical and desirable follow-on to existing LWRs [17]. Starting in 2002, NE released roadmaps that outlined a strategy to start building an advanced, non-light water design by 2017 [15–19]. While these roadmaps catalogue NE's progress in advancing the designs it supports, and occasionally provide timelines for eventual deployment, they rarely provide a systematic analysis of how to achieve NE's objectives.

To analyze progress since these seminal documents were published, we compiled all annual DOE budget justification documents, which detail funding down to the level of individual programs. We secured these

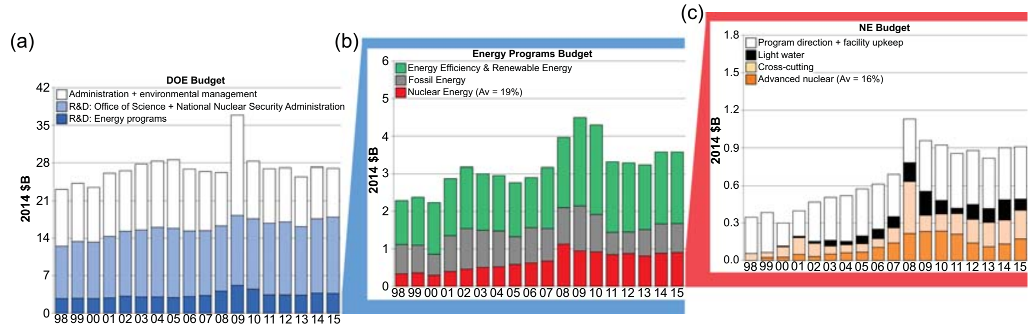

Figure 2. Level of funding for advanced reactors in DOE's overall budget. (*a*) DOE's annual discretionary budget is split between administration and environmental management (white), non-energy related R&D (light blue), and energy-related R&D (dark blue). (*b*) Energy-related R&D is divided among three energy offices, which include the Office of Nuclear Energy (NE, red). (*c*) NE's budget goes not only towards advanced reactors (dark orange), but also crosscutting technologies (light orange), light water reactors (black) and program direction and facility upkeep (white).

documents through a Freedom of Information Act (FOIA) request that yielded 400 000 pages of documentation. We isolated 20 000 pages that related specifically to nuclear energy R&D, and reconstructed the history of programs by building a database that traced both funding levels and changes in project names and designations. A similar database was constructed for the two other DOE energy R&D offices: the Office of Energy Efficiency and Renewable Energy (EERE) and the Office of Fossil Energy (Fossil). We also examined the level of fundamental R&D expenditures by reviewing annual laboratory-directed research and development (LDRD) budgets that describe this research by laboratory, project name, and funding level. These are national laboratory projects selected through a competitive process and dedicated to cutting-edge, high-risk R&D [31]. For both justifications and LDRD reports, two independent coders classified each budget line item as one that supports LWRs, advanced reactors or cross-cutting technologies. Next, we investigated the lifecycle of NE's major programmatic initiatives. While existing literature presents some elements of DOE's budget at a macro level, this detailed review of NE's budget constitutes our key contribution. Prior reviews have commented on the 'opaque' nature of DOE budget documentation [7]. We initially faced similar challenges, but eventually managed to reconstruct how NE's budget line items have evolved since 1998. All values reported in this paper have been converted to real 2014 dollars.

3. Results

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

Since 1998, DOE's discretionary budget has been between $23 and $29 billion, save for 2009, when it increased to $37 billion as a result of the stimulus package that increased spending across many government departments. As illustrated in figure 2(*a*), a substantial portion of the DOE budget goes to administration and environmental management. The portion dedicated to R&D has fluctuated between 50% (2009) and 66% (2015). In turn, most of that is dedicated to non-energy-related R&D, notably to the Office of Science and the National Nuclear Security Administration. Since 2000, these activities have consumed $8 to $11 billion of the annual DOE discretionary budget, their share varying between 55% (2009) and 69% (2005) of what DOE considers R&D spending. The $3 to $5 billion per year that DOE has spent on energy-related research (R&D: Energy programs in figure 2(*a*)) constitutes 10% (2005) to 16% (2008; 2010) of its annual budget.

DOE's R&D spending on energy programs is divided among the three offices shown in figure 2(*b*): along with NE, there is EERE and Fossil. Over the period we studied, NE averaged 19% of DOE's energy spending, EERE averaged 49% and Fossil averaged 25%. The money appropriated to NE is substantial—$670 million, on average—though, in our 18 year sample, it fluctuated by almost a factor of four between a minimum of $300 million in 2000 and a maximum of $1.1 billion in 2009.

Not all of NE's money is dedicated to the development of paradigm shifting technologies, such as advanced reactors. In fact, the office's activities can be broadly divided into three categories: first, sustaining the reliability and safety of the current LWR fleet; second, developing and deploying new fission technologies that promote nuclear power's viability; and third, maintaining infrastructure that enables the execution of DOE's missions related to weapons, non-proliferation, and nuclear research. Though these categories mirror NE's primary tasks, its official mission statement and funding focus has changed frequently, arguably driven by external political factors and reflecting a lack of programmatic discipline [30]. In figure 2(*c*), we report how NE's R&D spending has been allocated since 1998, classifying these expenditures by function.

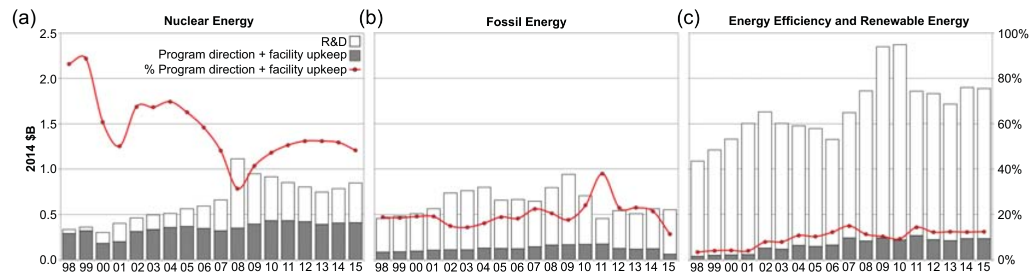

Figure 3. Program direction and facility upkeep in DOE's three energy offices. (*a*) NE spends an average of 57% annually on these tasks. (*b*) Fossil spends an average of 20% annually. (*c*) EERE spends an average of 10% annually.

On average, NE spends 57% of its annual budget on program direction and facility operations and maintenance, though year-to-year the fraction has varied between 30% and 90%. On average, only 15% of its budget has been spent on aspects of advanced fission research, development, and deployment. The amount has varied between $0 and $240 million per year. Over the 18 years we studied, NE has spent a total of $2 billion on non-light water research, which is just 0.7% of DOE's total R&D expenditure during that period. That said, DOE classifies nuclear weapons work as non-energy R&D; it is therefore fairer to describe this expenditure as the 4% of energy program R&D that it represents. Still, only part of this money has gone to advanced reactor design development; a portion ranging from 20% to 40% annually has gone to research on advanced fuels. Investing in advanced fuels research is critical to developing a new nuclear reactor technology. However, NE has mostly invested in one fuel type—tristructural-isotropic (TRISO) fuel—while exploring multiple reactor designs, most of which do not use that fuel.

To appreciate just how modest advanced reactor research expenditures have been, consider that recent estimates of the amount required to shepherd one advanced reactor technology through design completion and licensing exceed $1 billion; the full-scale demonstration of a new reactor technology is estimated to require anywhere from $4 billion [19] to $13 billion [32]. Hence, the total investment required to bring a new design to the point where it could be commercially developed and deployed is on the order of $10 billion. Given the history of cost overruns associated with new nuclear technologies, these estimates, which were spelled out in NE's advanced reactor roadmap and in subsequent reports [15–19], are likely to be optimistic. Either way, the total amount expended on advanced nuclear power by NE over the past 18 years—spread across multiple fuel types and technologies—has been substantially less than the government investment required to ready *one* non-light water design for commercial deployment.

The high costs that NE incurs on program direction and facility upkeep are due to the inherent expense of maintaining nuclear infrastructure. Idaho National Laboratory, for which NE is the lead office, has many facilities that collectively consume between a third and one half of NE's annual budget. Yet, as many have noted, it still lacks the advanced test facilities that would help accelerate qualification of the materials and fuels needed for many advanced reactor designs [33, 34]. While maintaining nuclear research infrastructure poses unique challenges, it is instructive to compare what NE expends on program direction and facility upkeep to that of the two other major offices that fulfill DOE's energy mission. It is more appropriate to compare NE to other energy offices than to the National Nuclear Security Administration or the Office of Science, since the latter two are not applied R&D outfits, and can justify their expenditure by appealing to national security or the importance of basic research. Figure 3 contrasts NE's budget allocation with EERE and Fossil. While NE has spent an average of 57% on program direction and facility upkeep over the past 18 years, Fossil has spent 20% and EERE has spent 10%.

3.2. Investigating laboratory-directed research and development

NE makes much of its investment in fundamental nuclear R&D through the national labs, and explicitly highlights its advanced reactor LDRD as a pillar of its strategy to accelerate their development [35]. Three of the nation's 17 labs—Argonne, Idaho, and Oak Ridge—can be characterized as incubators of innovative non-light water research. Sandia, Los Alamos, and Lawrence Livermore are primarily nuclear weapons labs. A further three—Brookhaven, Pacific Northwest, and Savannah River—do some fission related research but work primarily on LWRs or waste remediation.

For the three major advanced reactor labs—Argonne, Idaho, and Oak Ridge—figure 4 classifies the amount of LDRD funding dedicated to nuclear energy technologies in general, and to advanced reactors in particular. LDRD funds are competitively awarded to projects that are high-risk and potentially high-reward [31]. It is only a small portion of the total budget of each lab and, since the passage of the Consolidated Appropriations Act of 2014, any one lab's total expenditures on LDRD have been limited to 6% by statute [36]. But even at this fundamental research level, these three

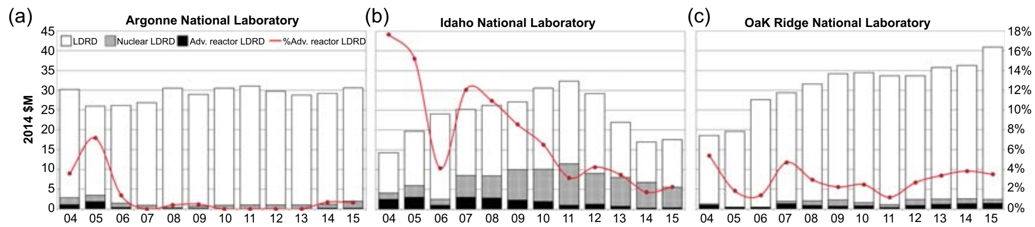

Figure 4. Laboratory-directed R&D on advanced reactors in the national labs. (*a*) At Argonne, advanced reactor LDRD has accounted for 1.2% of total LDRD over the past 12 years. (*b*) At Idaho, it has accounted for less than 8% of total LDRD. (*c*) At Oak Ridge, it has accounted for 3% of total LDRD.

centers of advanced reactor research have dedicated little effort to non-light water reactors. At Argonne, advanced reactor LDRD has accounted for an average of 1.2% of total LDRD. At Oak Ridge, the figure is 3%. And at Idaho—NE's laboratory—advanced reactor LDRD accounts for 7.5% of total LDRD. The big five non-light water laboratories have spent a total of $47 million on advanced reactor LDRD in the past 12 years, out of total LDRD expenditures—in all 17 national labs—of $6.5 billion (0.7%). Moreover, LDRD projects dedicated to advanced reactors cover a large number of technologies. At Argonne, half of advanced reactor LDRD projects since 2004 have been dedicated to the sodium cooled fast reactor and its fuel cycle. At Idaho, a quarter of advanced reactor LDRD projects have been focused on the gas-cooled reactor and TRISO fuel. At Oak Ridge, a third of LDRD projects have focused on molten salt technologies.

It is our assessment that the investment in different reactor technologies at different national laboratories is not the result of objective evaluations of the benefits and risks of various nuclear reactor designs. Instead, it represents an attachment to legacy investments, and an honoring of sunk costs, that is hard to justify in an era of tight budgets and critical clean energy needs.

3.3. Lifecycle of NE's major programmatic initiatives

Figure 5 lists major nuclear initiatives undertaken by NE over the past 18 years classified by reactor type, duration, and funding level. Three points stand out. First, numerically, more than half have been dedicated to advanced nuclear initiatives (top panel in figure 5): on average, these have lasted less than 5 years and cost less than $160 million each. Using DOE's own roadmaps as a guide [15–19], these are of neither the duration nor the funding level necessary to develop a non-light water reactor.

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

Third, one potential reason for the mismatch between spending and mission is rooted in political processes described elsewhere [30]. The only advanced nuclear initiative that has succeeded in creating a 'product'—which NE, as an applied R&D office, considers the ultimate measure of its success [30, 37]—has been the 'Advanced Fuels' program, which has achieved its goal of developing TRISO fuel particles, though even these are not yet available for commercial deployment. Notably, this is the only long-lived initiative, having received over $450 million over the past 18 years, but always in installments small enough ($35 million, on average) to avoid being targeted for termination by program officers, Congressional appropriators, or the Office of Management and Budget (OMB). While fuel is critical to the success of advanced designs, this program remains decoupled from reactor development. It is unclear from examining program documentation what role, if any, the fuel being developed will play in the transition to a non-light water reactor fleet.

Of the twenty initiatives in figure 5, seven are ongoing. Only three of the thirteen that have ended can legitimately be considered successes, as NE defines the term: NP2010 and the Advanced Fuels program have already been discussed; the third is the smaller Nuclear Energy Plant Optimization (NEPO) program. NEPO concluded in 2005, having succeeded in enhancing the reliability and availability of the aging LWR fleet.

4. Discussion

For many reasons, NE as it is currently structured has been unable to develop and deploy advanced, non-light water reactor designs. Our research shows that it has dedicated only $2 billion over the past 18 years to *all* advanced reactor and fuel initiatives, which by its own estimates is not enough to ready even *one* such design for commercial deployment. Reactor designs are being pursued at funding levels too low to be relevant to actual commercialization. Large sums have been

Figure 5. The Office of Nuclear Energy's major programmatic initiatives over the past 18 years. NE has funded advanced (top), crosscutting (middle) and light water (bottom) programs. The size of the bars reflects the amount of money appropriated to each program in each year. The mixed-oxide (MOX) plant appropriation is not included due to the distortive effect of its high cost (approximately $300 million) on figure size.

expended to maintain research infrastructure that only marginally supports NE's core mission. Much of this infrastructure also supports other programs, mainly related to defense, where research expenditures are even more removed from commercial opportunities. Decommissioning some of this infrastructure would likely incur high costs and further delay advanced reactor development. However, NE will remain liable for this infrastructure unless strong political backing catalyzes support for the shutdown of some facilities in order to free up funding for new, mission-relevant programs and infrastructure.

NE's strategy roadmaps assign the office a large role for developing advanced reactor designs to the point of commercialization, instead of the private sector [15–19]. The nature of novel nuclear technologies, and perhaps all energy technologies that exist at the frontier and thus require large investments to realize at scale, is that substantial government support appears to be required to undertake first-of-a-kind demonstration [28]. Still, this support can take many forms, and widely different models for project execution exist.

If we assume that, as a government R&D program, NE's primary role should be in developing advanced

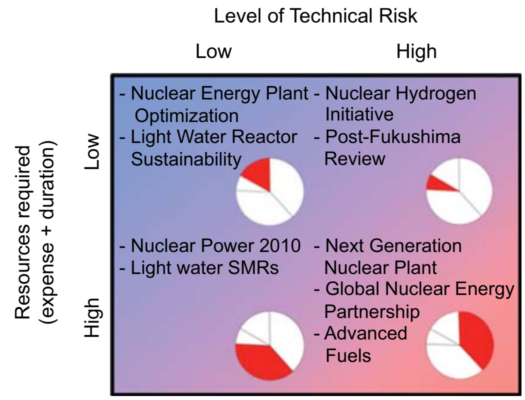

Figure 6. Fraction of NE's funding mapped to the continuum presented in figure 1. NE funds all regions of the continuum, assuming responsibility for evolutionary research that iteratively refines the existing paradigm. Pie charts reflect the portion of funding (for all programs, not just the examples given) dedicated to each quadrant of the continuum. We consider developments that are time-critical or of high import—such as planning and executing a combined industry and government response to a high-profile accident like Fukushima—to be complex undertakings that involve much room for error and a high level of technical risk.

reactor technologies, its funding profile does not seem to be congruent with that of a successful applied energy R&D office. In figure 6, we assign its programs to different regions in the continuum first presented in figure 1. Based on our analysis of its R&D spending, NE plays a substantial role across the entire continuum.

Substantial amounts of money have been dedicated to LWR research, which occupies the two quadrants on the left in figures 1 and 6 above. Some of this is conceivably crosscutting in nature and may require government support, but much of it—such as corrosion testing—probably should have been undertaken by commercial industry, the R&D arm of which has weakened [30]. Our analysis of the R&D being undertaken at the national laboratories—the ostensible incubators of innovation—shows that even they consider it part of their mission to iteratively improve the safety of light water technology. Much of their materials, fuels and modeling research is dedicated to ensuring the safety of operating reactors and to exploring life extension, instead of advancing novel technologies, as figure 4 demonstrates. While maintaining some competence in this field is important, by excessively playing this role, NE risks moving close to becoming a service provider for the light water industry. If industry lacks incentive to conduct this research in-house and transfers that mission to government, it is likely that Congress—under pressure from industry support groups—will fund it. However, perversely, the funder of last resort would have then become the funder of first resort.

Where NE does support truly innovative research that private industry has mostly ignored, our analysis of funding levels and focus shows that it is prone to changing priorities and terminating programs before they have achieved few if any of their objectives (figure 5). It is important to note that, while some line items in figure 5 appear to share similar goals, changes in program names often involve changes in officers, focus and mandate. Sometimes, they are internationalized or continue at low levels of funding. The clearest example is NGNP, where sensitivities to site location, technology choice and cost share eventually led to effective termination when no commercial partner could be found to continue the effort. Parts of NGNP survive as the NGNP Industry Alliance Limited. All government offices do this to some extent, and it is arguable that this behavior is a political asset in the short-term. However, there is a real risk that it might undermine NE's credibility and further erode political support for its mission. The policy ramifications for nuclear energy are stark, given that the mitigation window for decarbonizing the energy sector is, essentially, the next several decades [38].

5. Conclusions

In this paper, we do not seek to present a comprehensive diagnosis of the problems facing nuclear energy innovation in the US. Rather, we have reconstructed NE's budget history and evaluated how close the office has come to achieving its advanced reactor mission. Our research shows that, as currently structured, NE has neither the funding levels nor the programmatic focus that it needs to deliver on its mission of developing and demonstrating one or two advanced reactor designs by mid-century. This comes despite multiple strategy roadmaps and billions of dollars of appropriations. As acknowledged earlier, the sources of some of NE's problems are exogenous to the organization, the result of economic and political pressures to which it is subject.

Non-light water reactor technologies do not constitute the only viable future for nuclear power and we acknowledge the long and difficult history of these reactors. However, energy planners over the past six decades have advocated a transition from LWRs. More importantly, NE itself has elevated the development of these reactors to being a primary goal of the US nuclear enterprise, and persistently touts the comparative advantages of these reactors over the existing fleet of LWRs. This claim is contentious to some, but those who reject it would surely argue, like us, that NE's R&D agenda ought to be modified to reflect that fact.

Our conclusions about funding level and programmatic focus should inform debates on NE's future research activities, and can aid in the development of a solution to this problem. An array of earlier studies pointed to some of the challenges facing nuclear innovation in the US, though suggestions for improvement consist mainly of appeals to NE to better enable private enterprise's use of its facilities and resources [21]. Echoing the recently released report by the Secretary of Energy Advisory Board [32], our analysis suggests that the problem facing NE is sufficiently acute to warrant a new approach, perhaps after more extensive investigation. Much room exists for future research on the broad impacts of these budget fluctuations and lack of focus. Such fluctuations affect staff morale and, if they persist, could lead to a brain drain that would exacerbate already serious human capital constraints facing nuclear science and technology in the country. In general, more investigations of the political economy of energy and environmental innovation are warranted, given the wide range of impacts that political, socioeconomic, and institutional factors have on innovation.

Commercializing a new reactor technology would be an expensive, decades-long undertaking. Our analysis suggests that, absent a sense of urgency among NE and its political leaders—one that engenders the funding and focus required to develop and deploy a new nuclear technology—the likelihood that advanced reactors will play a substantial role in the transition to a low-carbon US energy portfolio around mid-century is exceedingly low. From a broader perspective, this failure also means that the US will cede its leadership on nuclear matters to other nations, limiting its ability to exert influence in key areas such as safety and security.

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