Title
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Journal
ENERGY POLICY, 108(Issues Sci. Technol. 32 2 2016)

ISSN
0301-4215

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Publication Date
2017-09-01

DOI
10.1016/j.enpol.2017.05.059

Peer reviewed

Energy Policy 108 (2017) 194–200

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

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

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ARTICLE INFO

Keywords:
Advanced nuclear
Advanced fission research
Energy transition

ABSTRACT

Deep decarbonization in the U.S. will require a shift to an electrified society dominated by low-carbon generation. Many studies assume a role for nuclear power in the new energy economy, and the nuclear industry anticipates an eventual transition from light water reactors to advanced, non-light water designs. The development of these advanced reactors is emblematic of the type of dramatic change that is needed to transition from fossil fuels and deeply decarbonize the energy system. The Office of Nuclear Energy (NE) in the U.S. is entrusted with the allocation of public sector expenditures for this transition, but there is little to show for its efforts; no advanced design is remotely ready for deployment.

Here, we report results from structured interviews we conducted with 30 nuclear energy veterans to elicit their impressions of the state of U.S. fission innovation. Most experts assessed NE as having been largely unsuccessful in enabling the development of advanced designs. The interview results highlight the importance of leadership and programmatic discipline, and how their absence leads to poor performance in driving change. Responses point to the likely demise of nuclear power and nuclear science in the U.S. without significant improvements in leadership, focus and political support.

1. Introduction

Deep decarbonization in the U.S. will require a shift to an electrified society dominated by low-carbon generation (Pathways to Deep Decarbonization, 2014). Many studies suggest that the most cost-effective way to do this is with a portfolio of technologies that include a role for nuclear power (Pathways to Deep Decarbonization, 2014; Lester, 2016; Dickenson and Sharp, 2013). However, the economic and institutional challenges facing large light water reactors (LWRs) make a rapid expansion in the use of current nuclear technologies difficult. For decades, energy planners have envisioned a move to standardized, factory-manufactured systems and non-light water designs, which would alleviate some of the challenges associated with LWRs, including their high cost and concerns about both safety and waste (Nuclear Energy Agency, 2009; Assembly of Engineering of the National Research Council, 1977; The National Academy of Engineering, 1979; Committee on Nuclear and Alternative Energy Systems, National Research Council, 1982). In the U.S., stewardship of this transition rests with the Department of Energy's (DOE) Office of Nuclear Energy (NE), an applied research and development (R & D) office charged with developing and demonstrating advanced reactor technologies (Department of Energy Office of Nuclear Energy Advanced Reactor Technologies Office Mission, 2016). Despite repeated roadmaps indicating a commitment to innovative designs, NE has failed to fulfill this mission, and no advanced reactor design is remotely ready for deployment.

In a recent analysis of NE's budget expenditures over the past two decades, we found that it lacks both the funding levels and programmatic focus to execute its non-light water reactor mission (Abdulla, et al., 2017). NE's difficulties in fulfilling its role highlight a fundamental challenge to major transitions in the energy system. How can limited government support for emergent energy technologies be allocated judiciously, and specifically, how can NE better enable nuclear innovation? Answering these questions ultimately requires expert judgment. Here, we report results from interviews we conducted with 30 senior nuclear energy veterans from across the enterprise—all with extensive knowledge of NE and the history of nuclear technology development—to elicit their impressions of the state of nuclear innovation in the U.S. and its likely future prospects.

2. Method

We conducted semi-structured interviews with subject matter experts that lasted two hours on average, making this one of the most

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http://dx.doi.org/10.1016/j.enpol.2017.05.059
Received 5 December 2016; Received in revised form 7 April 2017; Accepted 30 May 2017

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

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

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

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

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

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

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

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

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

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

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

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

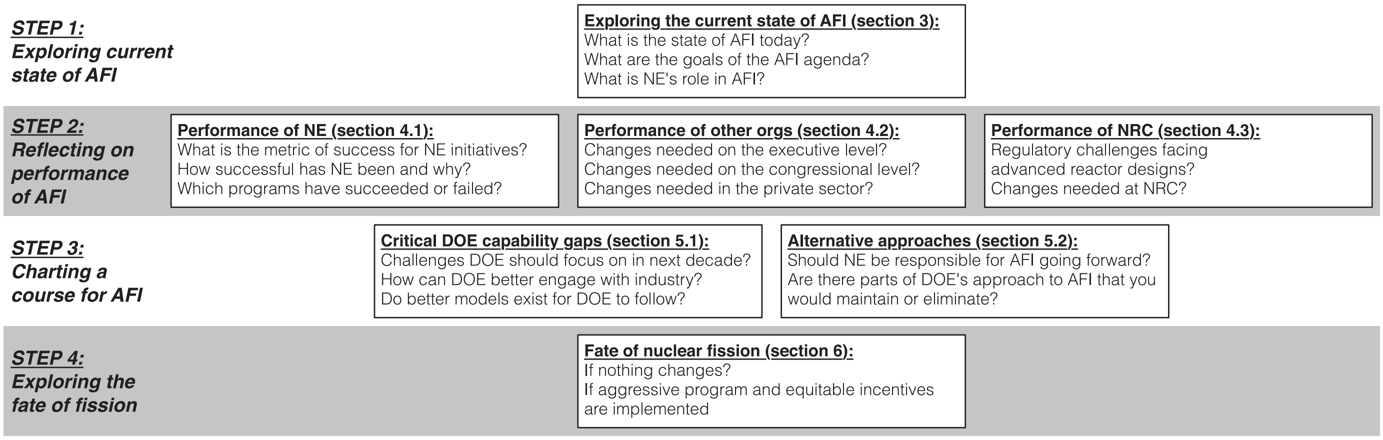

Fig. 1. Schematic outline of the topics covered in our interviews on the state of advanced fission innovation (AFI) in the U.S. Time runs from top to bottom.

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

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

4. Step 2: Reflecting on past performance in AFI

4.1. The Office of Nuclear Energy

While all organizations involved in the AFI enterprise have hindered innovation according to our experts, by far the greatest amount of criticism was directed at NE and the political establishment. Officially, one of NE's core missions is to support the development and demonstration of advanced, non-light water reactors (Department of Energy Office of Nuclear Energy Advanced Reactor Technologies Office Mission, 2016). Asked to gauge NE's success in this particular mission, the experts delivered a damning verdict, as shown in Fig. 2.

Part of this discussion was intended to elicit metrics of success with which to gauge NE's programmatic initiatives. As we note in the last section, most experts indicated that the ultimate metric of success was a deliverable "product." A deliverable product is one that sits high enough on the technological readiness level (TRL) for industry to pursue without extensive public support. The discussion was designed to evolve into one that assessed NE's major programmatic initiatives over the past two decades. The experts provided examples of initiatives they considered successes or failures, and there were far more examples of the latter. Seminal programs like the Global Nuclear Energy Partnership (GNEP), which ran from 2007 to 2008, and the Next Generation Nuclear Plant (NGNP), which was intermittently funded from 2005 to 2013, were judged abject failures. The reasons for failure differed in each case. In some cases, NE misjudged when and how to hand-off projects to industry; NGNP is a prime example of this. In others, participants indicated that NE micromanaged its grants to an extent that industry deemed intrusive. Some failures were caused by factors beyond its control: for instance, inflexible cost-sharing arrangements mandated by Congress and the Office of Management and Budget (OMB) make it difficult for industry to collaborate with NE. Even when the fault was not entirely its own, NE came in for withering criticism because of its lack of programmatic discipline. It rarely follows through on its advanced, non-light water reactor projects: it does not fund them at the level or duration necessary for project success, and it is attuned to political sensitivities, which means it often discards entire programs in favor of others that are more politically palatable. These faults are apparent in the budget analysis of NE we conducted earlier (Abdulla, et.al. 2017).

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

We offered the experts a closed list of causal factors that might explain NE's performance. Experts were asked to rank these by importance; we averaged these rankings, with 7 being the most important and 1 the least. Our results point to three factors being most critical: 1) shifting Congressional priorities, 2) shifting Executive priorities, and 3) the lack of consistent focus, vision and leadership within NE. Other factors, such as NE's funding level, the competence of

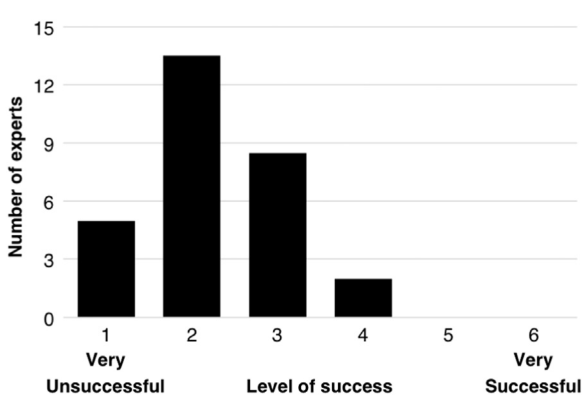

Fig. 2. Ratings of NE's success in supporting the development and demonstration of advanced, non-light water fission reactors were recorded on a six-point scale, ranging from very unsuccessful (1) to very successful (6).

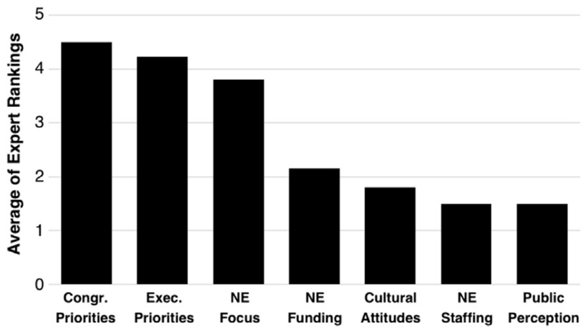

Fig. 3. Experts ranked the importance of factors that contribute to NE's performance on a scale of 1–7. We average their rankings here, such that the taller columns reflect more important factors.

its staff and the public's distaste for nuclear power occupied a distinctly second tier, as shown in Fig. 3. Most recognized that these factors were interrelated, and argued that the factors in the second tier are surmountable if the top three challenges are resolved. We did offer blank cards for participants to suggest alternative causes for NE's performance, but only one did so, adding "lack of market pull" as a distinct factor.

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

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

The experts lamented the fact that the U.S. nuclear enterprise finds itself in the unenviable position of being led by an organization that avoids taking risks and making hard decisions, frowns upon ambitious, long-term projects, funds them at a low level and is most concerned with the next appropriations cycle. On the other hand, the most aggressive of the new private entrants do make hard decisions, acknowledge that research takes time, spend large amounts of money on their projects and collaborate closely with nations that have the necessary facilities and a receptive environment for new development. One example that was noted repeatedly is the recent effort by TerraPower to team with major developers worldwide (World Nuclear News, 2016). This constitutes a reversal in the classical roles of government and industry, and points to a risk of pending irrelevance for U.S. R & D, as companies seek partnerships that lie outside its sphere of influence.

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

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

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

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

4.2. Industry and the wider federal government apparatus

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

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

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

4.3. The Nuclear Regulatory Commission

The complexity and cost of nuclear regulation has frequently been noted as a factor that stymies nuclear innovation (Lester, 2016). Given this, we expected the experts to be critical of the Nuclear Regulatory Commission (NRC), and some were. In general, however, the Commission emerged as a competent executor of its mandate, with many of its shortcomings due to factors beyond its control. There are two major problems with the NRC, according to interviewees. First, it is a light water regulator, with little to no current technical competence in regulating advanced reactors. But this is the entirely predictable result of how it is structured: since the mid-1990s, more than 90% of the Commission's budget has come from fees paid by plant operators. It is hard to justify expending tens of millions of dollars on establishing non-light water regulations to utilities (with active lobbying groups) that exclusively operate LWRs.

Second, the Commission is criticized for having a prescriptive, rule-based approach to regulation. Since these regulations are crafted with LWRs in mind, advanced reactors that circumvent light water's challenges—for example, designs that do not require expensive containment structures—are automatically disadvantaged. In the past, some have suggested that the Commission move to a risk-informed, performance-based regulatory framework. While the Commission's most recent roadmap embraces this (NRC Vision and Strategy, 2016), the experts criticized people who “parrot this line” at every meeting without “telling the NRC what they mean by it” or how it should be implemented.

5. Step 3: Charting a course for AFI

5.1. Critical DOE capability gaps

We asked the experts to list the challenges facing AFI in the U.S. in the next ten years. Three issues emerged as most critical. First is the ***diminished state of the technical infrastructure***. Most saw a clear need for improved facilities—chief among these a fast flux testing capability in order to qualify new fuels and materials. Currently, most of this testing is being done in Russia, in a facility that will soon be decommissioned. A new French reactor may provide some needed near-term capability. The experts, including several from the national laboratories, noted reluctance to explore the consolidation of facilities across DOE because of the political sensitivity of this process. In their judgment, consolidating facilities would free up funding for new infrastructure that might accelerate innovation and maintain U.S. technical leadership.

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

Third is the ***lack of evidence-based market signals*** that would value the benefits of low-emission nuclear power, just as it would other capital-intensive, low-carbon technologies such as carbon capture and sequestration (Talbot, 2014). While there was broad consensus that these challenges are critical to address for substantial progress to be made, none was deemed insurmountable in the presence of strong leadership.

5.2. Alternative approaches

The experts disagreed about how the U.S. ought to move forward. Four suggested that the national laboratories, where most government expertise lies, should lead. Ironically, this argument was not articulated by leaders within the laboratory system, despite the considerable patronage such a move would entail. Five suggested that universities should assume a greater leadership role, both in advancing basic research and in conducting social scientific analyses of nuclear power's sustainability. Seven suggested that NE, despite its problems, ought to lead the effort outright, while more than half believed that it should be a partnership between NE and industry. Most suggested that NE could still be salvaged if the political leadership prioritizes its mission, and if industry is supportive. Paralleling Winston Churchill's comments about democracy (Churchill, 1974), NE was judged to be the worst steward of the nuclear enterprise—except for all the others.

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

6. Step 4: Exploring the fate of nuclear fission

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

Twenty-seven out of thirty experts believed that, absent a dramatic improvement in focus and political support, the chances that the U.S. will develop a viable non-light water design in time to make a

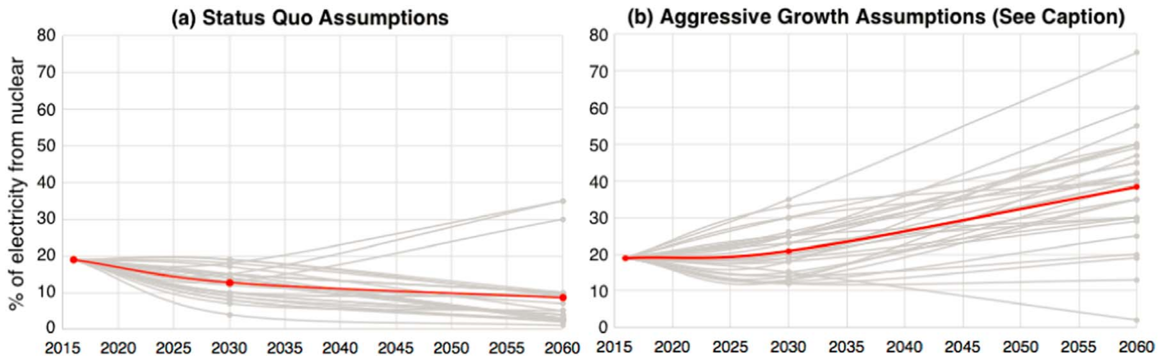

Fig. 4. (a) Expert assessments of the percentage of U.S. electricity generation that will come from nuclear power through the year 2060, assuming "status quo" R & D efforts and no dramatic changes in climate policy. **(b)** Experts are more optimistic about nuclear power's contribution to the electricity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

difference in carbon mitigation are low. Even with greater focus, the future viability of nuclear power in general is uncertain, given how energy markets inherently disfavor it. When asked to forecast the percentage of electricity that nuclear power will generate in the near (2030) and medium (2060) terms—under *status quo* assumptions—the experts drew curves that showed a gradual decline in generation, with nuclear power confined to the regulated markets of the southeastern U.S. Three outliers could not imagine that the U.S. would continue to ignore nuclear in its response to climate change, and predicted a bright future instead. In Fig. 4a, we outline their responses.

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

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

7. Conclusions and policy implications

Determining the level of government support needed for technology transitions is always challenging, given limited budgets and competing priorities. This is perhaps more difficult in a nuclear enterprise that has had a long history of government leadership, not just in basic research but also in reactor development and deployment. While most experts delivered a consistent diagnosis of the problems afflicting the enterprise, there was limited consensus on path and prospects for success moving forward. From a policy perspective, the implications are stark. Even with aggressive assumptions, experts indicate that advanced nuclear is unlikely to play a role in the timeframe necessary to deeply decarbonize the energy system and avert the worst consequences of climate change (Peters et al., 2015).

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

First is the need to consolidate existing infrastructure: the extensive, aging facilities that currently exist are of limited utility for advanced nuclear development. Experts recognize that this will face significant political opposition, much like that faced by the U.S. Defense Department with Base Realignment and Closure (BRAC) (Military Base Realignments and Closures, 2016). Research in advanced fission is spread across multiple national labs and universities. Consolidation that would free up the funding to develop the demonstration and test facilities the experts believe are needed might be extremely challenging.

Second, given the limited technical expertise within NE and the wide range of stakeholders vying for its appropriations, rigorous peer-review standards must be adopted to ensure each of NE's projects contributes to meeting its goal of supporting the development of advanced fission prototypes. Our experts indicate that NE is still an appropriate facilitator of these goals, but suggest including outside agencies such as the National Science Foundation in developing these standards and assessing progress.

Achieving these goals will require a coordinated effort and, while some still saw NE as the likely choice to lead, many felt that a new leadership approach was required given past dysfunction. As noted earlier, a number of experts recommended a significant change in the structure and mission of NE, advising that they move to a supporting role, enabling private sector innovation by making technical infrastructure and laboratory expertise more readily available. When coupled with a revised NRC regulatory approach, they felt this was a more prudent path that would avoid placing government in the position of driving or limiting market choice. This option has the advantage of being driven by the newest and most active of advanced reactor developers, who are trying to improve the prospects of nuclear energy in the U.S., and whose views are the most optimistic of those reported in Fig. 4.

Many of the more senior experts, who had lived through multiple reorganizations of the DOE NE organization, felt a more radical change in structure was needed. While they recognized that NE might still play a role, they believe overall leadership and oversight should come from a new, independent organization. This structure would be similar to the one spelled out by a recent Secretary of Energy Advisory Board Report (SEAB) (Secretary of Energy Advisory Board, 2016), which envisions a quasi-public corporation that would lead the effort, beginning by refocusing funding on a small number of advanced reactor initiatives. According to the SEAB report, this approach would first require a robust and transparent effort to down-select to just one or two promising technologies. NE would be intimately involved in the process, but in a shift from past efforts, an independent panel of stakeholders with strong political backing would lead the overall effort. According to the experts who supported this option, the benefits of such a process would be apparent to any who examine NE's "unfocused and unsuccessful" past funding for advanced reactor initiatives. While dedicated funding for fuels development and light water reactor sustainability have yielded successful products, advanced reactor funding patterns—spread over multiple technologies—have hampered development efforts over the past twenty years.

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

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

Funding Acknowledgments

This work was supported by the John D. and Catherine T. MacArthur Foundation through grant 12-101167-000-INP; the Center for Climate and Energy Decision Making, which is supported by the U.S. National Science Foundation (SES-094970); the U.S. Department of Veterans Affairs and Carnegie Mellon University Yellow Ribbon Program; the UC San Diego Frontiers of Innovation Scholars Program; the UC San Diego School of Global Policy and Strategy; and the Electric Power Research Institute.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.enpol.2017.05.059.

References

Assembly of Engineering of the National Research Council, 1977. Interim Report of the National Research Council Committee on Nuclear and Alternative Energy Systems. National Academies of Science, Washington D.C..

Abdulla, et al., 2017. A retrospective analysis of funding and focus in U.S. advanced fission innovation, Working Paper (in review).

Bush, V., 1945 Science, the endless frontier, a report to the President. US pGPO Washington, DC. p. 93.

Churchill, W., 1974. Speech, House of Commons, November 11, 1947.—Winston S. Churchill: His CompleteSpeeches, 1897–1963. James, Robert Rhodes (ed.), Vol. 7, p. 7566.

Committee on Nuclear and Alternative Energy Systems, National Research Council, 1982. Energy in Transition 1985-2010. p. 210(fission); p. 385(fusion).

Department of Energy Office of Nuclear Energy Advanced Reactor Technologies Office Mission, 2016. Statement accessed 29 August 2016 at ⟨http://energy.gov/ne/nuclear-reactor-technologies/advanced-reactor-technologies⟩.

Dickenson, B, Sharp, P, 2013. The Future of the U.S Electricity Sector. Energy Policy Forum; Aspen, CO. The Aspen Institute Energy and Environment Program.

H.R. 590, 2017. Advanced Nuclear Technology Development Act of 2017. Accessed 01 April 2017 at: ⟨https://www.govtrack.us/congress/bills/115/hr590/text⟩.

Lester, R.K., 2016. A Roadmap for U.S. Nuclear Energy Innovation. Issues Sci. Technol. 32 (2), (Winter 2016).

Military Base Realignments and Closures, (Internet) US Government Accountability Office Issue Summary. 2016. [accessed 01 December 2016] Available at: ⟨http://www.gao.gov/key_issues/realigning_closing_military_bases/issue_summary#t=0⟩.

NRC Vision and Strategy: Safely Achieving Effective and Efficient Non-Light Water Reactor Mission Readiness (Draft downloaded 19 October 2016 from ⟨https://www.regulations.gov/document?D=NRC-2016-0146-0002)⟩.

Nuclear Energy Agency, 2009. Strategic and Policy Issues Raised by the Transition from Thermal to Fast Nuclear Systems; Organization of Economic Co-operation and Development Nuclear Energy Agency No. 6352.

Pathways to Deep Decarbonization, 2014. Sustainable Development Solutions Network (SDSN) and Institute for Sustainable Development and International Relations (IDDRI), 2014 Report. p. 7.

Peters, G.P., et al., 2015. Measuring a fair and ambitious climate agreement using cumulative emissions. Environ. Res. Lett. 10 (10).

Secretary of Energy Advisory Board, 2016. Secretary of Energy Advisory Board Report of the Task Force on the Future of Nuclear Power. U.S. Department of Energy.

Talbot, David, 2014. Carbon Sequestration: Too Little Too Late? MIT Technology Review, October2014. Last accessed 21 October 2016 at: ⟨https://www.technologyreview.com/s/531531/carbon-sequestration-too-little-too-late/⟩.

The National Academy of Engineering, 1979. The Outlook for Nuclear Power; Presentations at the Technical Session of the Annual Meeting.

World Nuclear News, 2016. TerraPower, CNNC team up on travelling wave reactor. Accessed 02 September 2016 at ⟨http://www.world-nuclear-news.org/NN-TerraPower-CNNC-team-up-on-travelling-wave-reactor-25091501.html⟩; Weaver, K., 2016. Presentation at the NRC-DOE joint workshop on advanced non-light water reactors (last accessed 19 October 2016 at: ⟨http://www.nrc.gov/docs/ML1618/ML16188A226.pdf⟩).