Across the "Second Valley of Death": Designing Successful Energy Demonstration Projects

BY DAVID M HART | JULY 2017

Technology demonstration projects pose one of the most difficult challenges in energy-innovation policy. They are necessary to build an adequate portfolio of clean-energy options that have the potential to be deployed globally on a massive scale in the coming decades. They require public investment; private investors will not fully fund them. But the federal government's track record of selecting, funding, and managing these projects is not encouraging. The title of the leading study of the subject, *The Technology Pork Barrel* (which was published in 1991 and based on projects carried out in the 1970s and early 1980s), conveys its conclusion: Demonstration projects almost inevitably become "technological turkeys."[1]

The United States should build and sustain a robust, diverse portfolio of technology demonstration projects as part of a comprehensive clean-energy innovation policy. Its current portfolio is not robust, and it is rapidly dwindling.

Defying this quarter-century-old conventional wisdom, the Obama administration initiated the first major new energy technology demonstration program in decades. (In the technology maturation process, as described in more detail below, demonstration falls between R&D, which is typically done with grant support at universities or national labs, and commercialization, which may involve tax breaks or government loan guarantees.) The performance of the Department of Energy (DOE) in running this program, which is explored in this paper, is somewhat more encouraging than *The Technology Pork Barrel* would lead one to expect, particularly in terminating underperforming projects. But the Obama-era experience does not provide full confidence that the challenge will be met by DOE in the future. Significant reform of DOE's approach to demonstration projects remains in order, and Congress should consider whether to set up a new agency to run some of these projects instead of DOE.

ITIF's study of 53 energy technology demonstration projects that were initiated between 2009 and 2011 yields the following recommendations and findings.

- The United States should build and sustain a robust, diverse portfolio of technology demonstration projects as part of a comprehensive clean-energy innovation policy. Its current portfolio is not robust, and it is rapidly dwindling.
- The federal government should continue to co-invest with private partners in clean-energy demonstration projects, because such projects yield public benefits and because private investors lack adequate incentives to bear their full costs. The 2009 stimulus package, which funded the most recent round of projects, was a good investment mechanism because it imposed a sunset date on project completion and did not require annual appropriations to sustain projects.
- Private sector partners, especially technology end users, should continue to take leadership roles in implementing clean-energy demonstration projects. The operational experience gained by these partners is a key benefit that motivates their investment in the demonstration and enables full commercialization of the technology after it has been demonstrated.
- Federal policy for private co-investment in demonstration projects should become more flexible in order to accommodate varying risk profiles, resulting in a wider range of cost-sharing ratios across projects. These ratios have clustered in the past around arbitrary levels established by Congress.
- Federally funded clean-energy demonstration projects should make information sharing among all potential users of the demonstrated technology a higher priority than it has been in the past and incorporate it into project metrics and evaluation criteria. Although such information sharing may reduce the incentive for private partners to invest in demonstrations, it accelerates diffusion and enhances competition as the technology is being commercialized.
- Initial selection of clean-energy demonstration projects should avoid excessively rapid scale-up of unproven technologies and overly optimistic assumptions about the economic and policy environment for follow-on investments in them. The Obama administration's record was uneven in both respects.
- Federal policymakers should remain prepared and willing to terminate unsuccessful demonstration projects. The experience of the past decade suggests that the "technology pork barrel" syndrome, in which unsuccessful projects lived on because they provided local economic benefits, is not inevitable, but it remains a real possibility for large projects.
- Although DOE improved its performance in designing and managing demonstration projects compared to the 1970s and 1980s, a continuing effort should nonetheless be made to explore the viability of establishing alternatives in this domain, such as the proposed Energy Technology Corporation and Regional Innovation Demonstration Funds (see box 3 below). The factors that facilitated

termination of unsuccessful projects in the Obama period may be short-lived, and DOE has not put questions about its management capability to rest.

- Federal agencies other than DOE, such as the Departments of Defense and Transportation, as well as regions and states, should consider making their own co-investments in clean-energy demonstration projects.

The paper begins by very briefly reprising the case for federal clean-energy innovation policy. The following sections explain why demonstration is essential to successful innovation in many areas of energy technology and why the private sector, quite rationally, is unenthusiastic about investing in this stage, leading it to be labeled the "second valley of death" (the first lying between research and prototype). The paper then turns to the scholarly literature on demonstration projects in general as well as the history of federally funded energy technology demonstration projects in particular to develop a set of design principles. These principles are applied to the Obama-era portfolio to provide an early assessment of its strengths and weaknesses, leading to the conclusions summarized above.

THE CASE FOR CLEAN-ENERGY INNOVATION POLICY

The Information Technology and Innovation Foundation (ITIF) has made the case for a robust federal clean-energy innovation policy on many occasions.[2] The short version of these arguments takes the reader through several steps in a logic chain:

1. Global warming is real, human-caused, and problematic.
2. Avoiding the worst consequences of global warming requires that greenhouse-gas emissions be reduced to near zero.
3. Getting to near zero greenhouse-gas emissions requires a transformation of the energy system.
4. The success of this transformation depends on clean energy being cheaper and better than dirty energy.
5. The only way for clean-energy technologies to become cheaper and better is through a worldwide innovation push, in which the United States government must play a leading role.[3]

Points 4 and 5 provide the major premises for this paper, and they are developed in much greater detail in other publications.[4] The argument has been reinforced recently by analyses of deep decarbonization that model zero-emission scenarios. One recent review of 30 such studies concluded that reaching zero emissions requires a significantly different mix of energy resources, many of which are not yet commercially viable, than the mix that would achieve more modest emissions reductions of 50 to 70 percent.[5] Innovation policy is vital to avoid locking in massive suboptimal investments of technologies that are already mature or, more likely, failing to achieve the needed reductions altogether.

DEMONSTRATION: A CRITICAL STAGE OF ENERGY INNOVATION

Demonstration is an especially important stage of the clean-energy innovation process. It is very difficult to anticipate how well many full-scale energy systems will operate based only on the performance of smaller-scale prototypes. Potential innovators must therefore shoulder the cost and risk of building and operating a full-scale, first-of-a-kind demonstration project, a process that often takes several years and substantial sums of capital, before being able to move to a commercial basis. This section sets forth several reasons for this difficulty.

Models of innovation often portray the innovation process as a series of stages that begins with an invention or research finding, moves through development, and concludes with commercialization. (See figure 1.) This "linear model" has been roundly and rightly criticized. The process is much more interactive across the stages than the linear model implies. Market demand, for instance, often exerts a pull on researchers that focuses their attention on specific problems. Similarly, tradeoffs that must be made when engineers consider how a new product is to be manufactured usually have consequences for both research and commercialization. (See figure 2.)

Figure 1: Linear model of innovation[6]

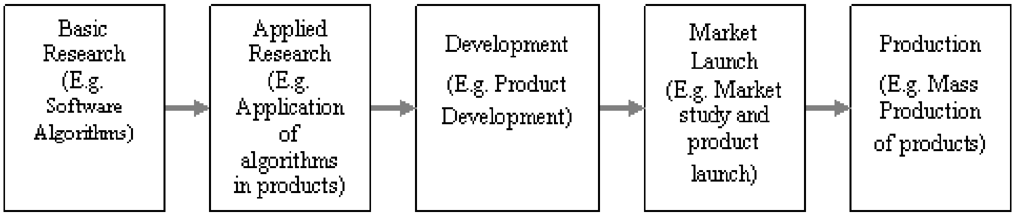
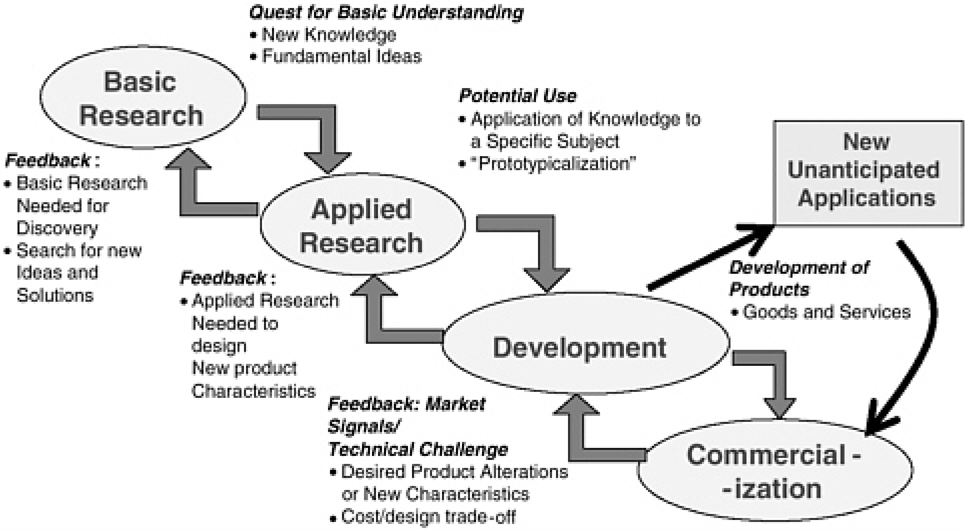


Figure 2: Feedback effects in the innovation process[7]



As energy-innovation researchers have sought to move beyond the linear model, they have argued intensely about what the middle stages of the process look like. Where simple models merely have "applied research" and "development" between "basic research" and "commercialization," more sophisticated ones include steps such as "analytic design," "proof of concept," "prototyping," "pilot plants," "field trials," and "demonstration." This "muddle in the middle" stems from an effort to overgeneralize about the innovation process, which varies greatly across technologies.

One conceptual framework that helps to clarify this debate distinguishes between complex systems and commodity goods.[8] Complex systems are composed of many subsystems, draw on a diverse knowledge base, and often must be customized during deployment. Commodity goods are assembled from standardized components, involve less tacit knowledge, and can be mass-produced. The middle stages of the innovation process for complex systems depend more heavily on full-scale demonstration projects and, often, pilot plants of intermediate scale as well, than they do for commodity goods.

Among energy systems, nuclear power is a good example at the complex-systems end of this conceptual spectrum. An innovative nuclear power plant involves millions of components and thousands of designers and builders. Solar panels may seem to lie toward the commodity-goods end of the spectrum: An innovative solar panel may plug into the same frame and wiring as an older one. Yet, the distinction is not quite so simple. The factories in which the innovative solar panels are built can be quite complex, as can the power grid into which these panels are inserted.

There are a number of reasons why complex systems, especially complex energy systems, typically need to be demonstrated before they can diffuse widely. One is the challenge of integrating their numerous and diverse components and subsystems. These may interact in unexpected ways at full-scale that cannot be anticipated at the laboratory bench or even in pilot plants. This challenge has vexed the Kemper, Mississippi, demonstration plant that combines coal gasification, carbon capture and use, and combined cycle power generation. "[T]he large increase in project costs ...," writes MIT's Howard Herzog, "can be attributed to implementing multiple first-of-a-kind technologies and the complexity of integrating them together."[9]

Energy systems, especially electricity systems, are also usually "tightly coupled," to use Charles Perrow's phrase.[10] Failure in one component of a tightly coupled system is more likely to cause the entire system to fail than a similar component failure in a loosely coupled system. Information technology firms like Google can beta test unfinished products on willing customers because the consequences of failure are limited; these early-adopting volunteers serve as the demonstration test bed to debug this loosely-coupled system. Failure of a power plant or an electric grid, by contrast, may have cascading impacts that cripple a city or region. Demonstration projects allow innovations that must be integrated into tightly coupled systems, such as IT-intensive "smart grid" technologies that optimize management of electric power transmission and distribution, to be debugged in more controlled settings than beta testing them on the public.

Another reason why demonstration is so important in complex system innovation is that it reduces economic risks for follow-on projects. Very large systems, such as offshore-wind farms or new nuclear power plants, may be "bet-the-company" plays for their owners. Their shareholders are likely to be loath to approve them without confidence that such a bet will not be lost. Demonstration projects that establish cost, reliability, and performance characteristics of the full-scale system in operation may provide this confidence. These characteristics are particularly important for innovation in legacy markets such as electricity and transportation, as William Bonvillian and Charles Weiss point out, because end users are unlikely to be willing to pay a premium for the commodity services they provide.[11] New systems that provide such services need to be economically competitive from the get-go, as opposed to gaining market share because of higher quality or other consumer functionality.

Finally, innovative energy systems may present institutional risks that demonstration projects may reduce along with technological and economic risks. Regulators may be unfamiliar with the innovation and need to develop new procedures to manage it. The public may have fears about it that a demonstration can help put to rest. Environmental or safety concerns might need to be worked out. Concentrating solar-power installations in fragile desert environments, for instance, may pose environmental risks, while smart-grid technologies that collect "big data" about energy use may raise concerns about privacy and security. Demonstration projects may therefore create value by establishing public confidence in the technology along with economic viability.[12]

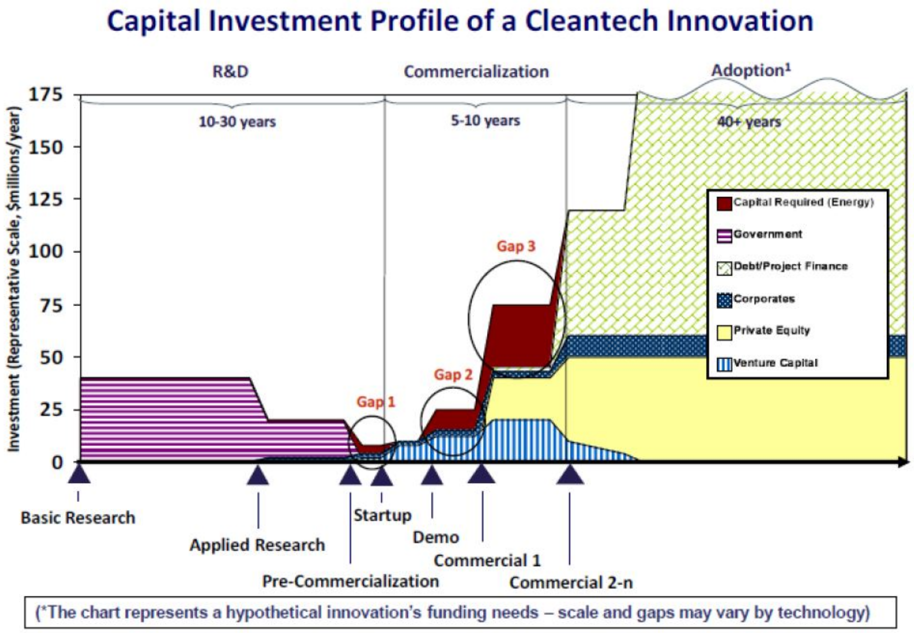
Demonstration projects for complex energy technologies, then, are often compelled by the challenges of systems integration, tight coupling, and reduction of economic and institutional risks. Without such projects, the energy-innovation process is likely to founder. As MIT's John Deutch has put it, "energy innovation is constrained not by an absence of new ideas, but by the absence of early examples of successful implementation."[13]

BARRIERS TO PRIVATE INVESTMENT: THE "SECOND VALLEY OF DEATH"

Because of the significant negative externalities from dirty energy, the public interest would be served if technology-demonstration projects that seek to provide new options for clean energy go forward. However, the private sector is generally unwilling to bear their full costs. This reluctance is not irrational. Some of the same challenges that make demonstration an essential stage in the energy-innovation process also deter private investors. So does uncertainty about future energy policies and the prospect of free riding by competitors of any firm that chooses to bear the full cost. None of the well-established private solutions for managing risk and uncertainty, such as portfolio management by individual firms, venture capital investment, or industry-wide cooperation, fully overcome these deterrents in most cases. Many potential demonstration projects therefore go unfunded, falling into what some analysts have termed the "second valley of death."[14]

The original idea of a "valley of death" arose from the linear model of innovation. If basic researchers have a good idea for a new technology, according to this model, they are supposed to hand it off to a firm that can develop it into a marketable product. The time, cost, and risks of the development phase, however, frequently deter investors, leaving many good ideas to die in this valley.[15] More sophisticated innovation models have elaborated this analysis while retaining the metaphor. In the case of complex energy technologies, innovators may face multiple moments in which cost and risk jump abruptly while reward is deferred, threatening their existence. Cleantech venture investor Will Coleman, for example, identifies three such valleys: start-up, demonstration, and initial scale-up.[16] (See figure 3.)

Figure 3: Three valleys of death in cleantech innovation[17]



As the previous section has shown, the costs and risks of demonstrating complex energy innovations are high relative to many other fields of technology, deepening the second valley of death. The rewards to the innovator, by contrast, are less certain and potentially lower, making the path out of the valley even steeper. One reason for the steep walls of the valley is that public policy may change during the demonstration phase, unexpectedly altering investors' payoff. Energy is a heavily regulated sector to begin with, and climate concerns have added new layers of policy in recent decades, particularly subsidies, mandates, and taxes. A demonstration project that pencils out when one political party is in power may not do so when another replaces it and changes the policy mix.[18]

The prospect of free riding also reduces the expected reward for investing in demonstration projects.[19] Such projects are intended to show potential users that an innovation can work in practice. Yet, by doing so, they generate knowledge about technological configurations, operating procedures, and other technical and managerial details that may become available to firms that do not invest in demonstrations. These free riders, who may include international as well as domestic competitors, may then be able to replicate the innovation at a lower overall cost than the demonstration project's investors. The prospect of free riding in such a situation deters investment, a phenomenon well known to scholars of basic research and invention, which are plagued by the same market failure.[20]

Intellectual property (IP) rights sometimes solve the free-rider problem sufficiently to induce investment in risky projects. In the pharmaceutical industry, for example, firms are willing to carry the extraordinarily large costs of clinical trials, which serve a purpose similar to energy technology demonstration projects, because they are able to secure and enforce legal protection for new drugs. This solution is less effective for complex energy technologies. Patents in this area are narrower and more easily "invented around" than in pharmaceuticals, making them less valuable.[21] If General Electric were to demonstrate a new type of power plant, it would be less able to use IP protection to defend it from Mitsubishi, Siemens, and other competitors than would a similarly placed drugmaker.

Venture capital is another institution that could, in principle, bridge the second valley of death. Venture capitalists (VCs) specifically seek out opportunities that are too risky for banks or institutional investors to fund. However, they typically seek higher rewards than most clean-energy technologies can provide, and on a quicker timetable. In addition, the high cost of many large-scale energy technology demonstration projects would stretch the budget of all but the most deep-pocketed VCs, making it difficult to assemble a portfolio of investments that would limit the risk from any one project. As a result, a recent MIT study concluded that venture capital is "the wrong model for clean energy innovation."[22]

Some large firms have the resources and patience to undertake projects that scare away even VCs. The builders of large passenger jets famously "bet the company" on new models that take years or even decades to pay off, such as Boeing's 787 and Airbus's A380. But these kinds of investments are in competitive, innovation-based industries where the failure to innovate often means the death of the company. Although multibillion-dollar investments with long time horizons, such as new oil fields, power plants, and transmission lines, are common in the energy industry, they rarely lead to significant innovation. Incumbent energy providers are usually just doing what they already know how to do. Unlike in the aircraft or semiconductor industries, not innovating in the energy industry poses little risk to firms, in part because energy is a commodity. Moreover, the rewards that accrue to energy innovators may be limited by regulators as well. This risk/reward ratio contributes to a culture of technological conservatism in much of the energy industry.

A final potential mechanism for raising private funding for energy-demonstration projects is the industry-wide consortium. If all firms gain from advancing a technology, all may see the value of collaborating to contribute to its development. The U.S. semiconductor industry, which faces enormous new capital investments with each new generation of chip-fabrication plants, has successfully created industry-wide research and technology development entities, such as Sematech and the Semiconductor Research Corporation, to spread some of these early-stage risks. Such collaborations among erstwhile competitors are difficult to organize, however. The semiconductor industry was compelled to collaborate by the existential threat posed by imports in the 1980s and has been aided by U.S. Department of Defense (DOD) funding. Industry-wide R&D consortia, such as the Electric Power Research Institute and Gas Technology Institute, exist in the energy sector, but they have shrunk in scale and scope as deregulation and restructuring deprived participating firms of discretionary funding to support them.[23]

Indeed, when it comes to pollution-control technologies, firms may have disincentives to collaborate in this fashion. In the 1960s, U.S. auto firms colluded to suppress emissions-control technologies, rather than develop them, even though promising pathways were clearly available.[24] Key environmental laws, such as the Clean Air Act, set standards based on the "best system of emission reduction" that has been "adequately demonstrated."[25] If no such demonstration has been made, then weaker standards must be set, providing the incentive to avoid demonstration projects.[26]

These "fundamental, structural market shortcomings," in the words of *Bloomberg New Energy Finance*, "cannot be resolved by the private sector acting on its own. … it is only with the public sector's help that the Commercialization Valley of Death can be addressed."[27] A recent study of 511 demonstration projects by Gregory Nemet of the University of Wisconsin and his colleagues, which spanned decarbonization in the energy and industrial sectors, found that almost all of those for which data could be found involved a financial contribution from the public sector. The median public share of funding was 64 percent.[28]

While firms and industries may benefit from their own investments in energy technology demonstration projects, these benefits are too meager or uncertain to outweigh the costs and risks, especially when taking in the considerable positive externalities. For the public benefit from such projects to be realized, the public sector generally must share the financial burden and invest along with potential private beneficiaries. A full portfolio of public investments in energy innovation should include demonstration projects as well as basic research, applied research, and development projects.[29] As Resources for the Future president Richard Newell, ordinarily no fan of public subsidies for energy producers, put it, "there may be a compelling rationale for well-designed public support for a limited number of first of a kind mitigation technology projects, so long as the purpose is the generation of substantial new knowledge."[30]

AVOIDING "WHITE ELEPHANTS": DESIGN PRINCIPLES FOR PUBLICLY FUNDED CLEAN-ENERGY DEMONSTRATION PROJECTS

The rationale is compelling, and the prospect of a publicly paved pathway through the second valley of death is tantalizing. But Newell's caveats, notably that public support be "well designed," should be taken seriously. The Department of Energy has a "checkered history" with demonstration projects that includes (as Richard Lester and this author have put it) many "white elephants": expensive projects that did not lead to follow-on investment.[31] This history, as well as analyses of experience with demonstration projects outside the United States, yields several design principles for energy technology demonstration policy that are developed in this section.

Linda R. Cohen and Roger G. Noll's 1991 book, *The Technology Pork Barrel,* dominates the literature on federally funded technology demonstration projects in the United States.[32] Their thesis is that such projects rarely succeed in bridging the gap between proof of principle and market viability. Once a project's spending spigot is turned on, its geographically concentrated fiscal benefits attract political support without regard to technological payoffs or commercial viability. Large projects, in particular, are attractive to legislators whether or not the technologies being demonstrated are ready to be scaled up and even if cost, schedule, and performance targets are consistently missed. According to this view, white elephants are a virtually inevitable outcome of the U.S. political system.

The paradigmatic case for Cohen and Noll is the Clinch River Breeder Reactor Demonstration, "the quintessential technological turkey by the time it was mercifully put to rest" in 1983, as they put it.[33] Breeder reactors produce fuel even as they produce electricity, promising an inexhaustible energy resource. But they have not proven to be economically viable, nor have concerns about their safety and nuclear proliferation been dispelled. The Clinch River project ran for 14 years, absorbed more than $5 billion, and was never completed. Cohen and Noll show that promoters in government and industry oversold the technology and that the project was sustained because it provided contracts and jobs, even as it displaced more meritorious R&D projects.

Cohen and Noll's analysis of the synthetic fuels (synfuels) program of the same era, which spent about $2 billion without achieving its objectives, follows a similar pattern. Only the program's inability to spend enough money quickly enough "saved the program from being a larger fiasco than it was."[34] Although Cohen and Noll conclude their study with a set of recommendations, emphasizing that the decision-making processes for R&D and demonstration should be institutionally separated, they are pessimistic that such steps would "dramatically raise the batting average of R&D commercialization projects."[35] *The Technology Pork Barrel*'s clear message and long shadow contributed to what energy-innovation scholars Laura Diaz Anadon and Gregory Nemet term "the U.S. government's aversion to large-scale demonstrations" between the Reagan and Obama administrations.[36]

Yet, as Anadon and Nemet pointed out when they revisited the synfuels case in 2014, this interpretation risks throwing the baby out with the bathwater.[37] Like the breeder reactor program, the synfuels program ran into market headwinds (notably dropping oil prices) that very few forecasters anticipated, which aggravated flaws in the program's design. Despite these flaws, the program managed to establish the viability of technologies that came into commercial use during the two decades after *The Technology Pork Barrel* was published. MIT's Deutch even argues that the Synthetic Fuels Corporation (SFC), which was established in 1980 to manage some of the synfuels program's projects, should serve as a model for future demonstration programs. SFC was endowed by Congress with greater flexibility in hiring and project selection and support than DOE, allowing it to bring projects in on time and under budget.[38] (See box 3 below.)

Stanford's John Weyant sums up this line of thought: Cohen and Noll leave "a surprisingly large amount of room for optimism in the current environment."[39] Rather than give up on publicly funded energy technology demonstration projects and thereby eliminate important options for accelerating clean-energy innovation (or relying on other countries to demonstrate such options), the federal government should design and manage such projects better. The scholarly literature on demonstration projects suggests five principles to guide this process.[40]

Rather than give up on publicly funded energy technology demonstration projects and thereby eliminate important options for accelerating clean-energy innovation (or relying on other countries to demonstrate such options), the federal government should design and manage such projects better.

First, as *The Technology Pork Barrel* makes clear, the process of selecting, funding, and shutting down demonstration projects should be insulated from political influence. Demonstration projects should only proceed when smaller-scale pilots and trials have proven that they are warranted, following what Chris Hendry of City University London and his colleagues call a "coordinated sequential approach" to technology development.[41] They should be subject to strong, independent technical oversight, so that emergent issues do not hemorrhage into budget- and schedule-busting pathologies.

Second, the costs of demonstration projects should be shared between public and private investors in rough proportion to the benefits that they provide to the two sectors.[42] Although the operational and reputational benefits of involvement in such projects do not generally justify private participants bearing their full costs and risks, these benefits are not negligible either. Participation may provide significant first-mover advantages in the ensuing commercial-market competition. Private investment is also a key mechanism for oversight and insulation from political influence, and a signal of a project's technical and economic viability. Private "skin in the game" reduces the risk that projects will be sustained for pork-barrel reasons. If the private share of a demonstration project's financing cannot be sustained, the public's contribution should be halted as well.

Third, demonstration projects should engage all segments of the innovation and value chain that would need to be involved in fully commercial versions of the technology. As Hans Hellsmark of Chalmers University in Sweden and his colleagues put it, demonstration projects "should be purposefully used to create alliances among actors along future value chains that have the capacity to develop new technology."[43] In the demonstration of an electricity-generating unit, for instance, the participants ought to include equipment manufacturers, utilities, and industrial or government laboratories, at a minimum. Demonstration projects are meant in large part to solve systems-integration and institutional challenges, and these solutions typically require learning by doing and organizational adjustment. Unless the same kinds of organizations are involved in the demonstration that will be involved in commercial operation, such learning may well be lost in the post-demonstration phase.

Fourth, demonstration projects should foster open exchange of performance and cost data.[44] Along with actually solving technical and institutional challenges, demonstration projects should certify these solutions publicly and thus provide confidence that the technologies being demonstrated warrant wholly private follow-on investment. Keeping data proprietary weakens this certification function, mutes competition in the follow-on phase, and limits external oversight. It is true that adhering to the principle of openness reduces the private benefits of investment, but it does not eliminate them. Investors still benefit from acquiring hands-on tacit engineering knowledge, relationships, and goodwill. Nonetheless, this principle implies a relatively larger public share in project finance than would otherwise be the case.

Finally, demonstration projects should only be undertaken if there is a reasonable expectation that there will be a supportive environment for follow-on investment.[45] The knowledge generated by these projects, especially tacit knowledge, may be lost if it is not put to use again reasonably quickly in the next generation of projects. The breeder reactor and synfuels cases show that predicting the environment that will obtain at the end of a project is difficult. "[D]emonstration programs," write Nemet and his colleagues, "need a plan for robustness, so that projects have a chance to proceed to commercial adoption under a range of market outcomes, not just optimistic ones."[46] Deployment policies, such as technology-forcing regulation or tax incentives, may aid technologies in climbing the steep demand-side of the second valley of death, especially if such policies are present across diverse jurisdictions, diluting the risk that they may be removed due to changing political circumstances in one country or state.

CLEAN ENERGY DEMONSTRATION PROJECTS UNDER THE OBAMA ADMINISTRATION: AN INITIAL ASSESSMENT

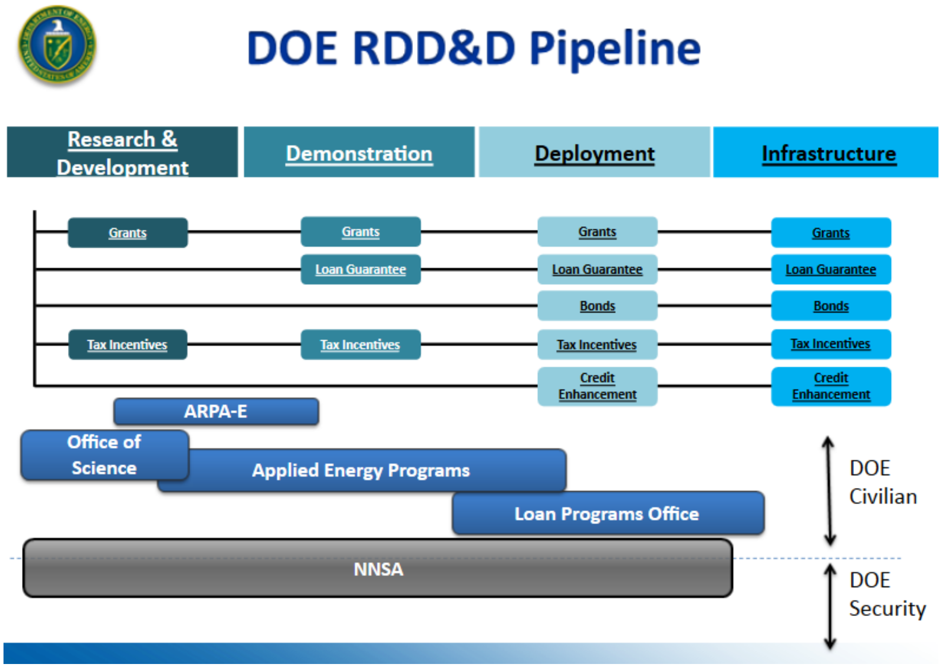
The Obama administration accepted the arguments that innovation is essential to facilitate the transition to a clean-energy system, that demonstration projects are necessary to foster energy innovation, and that such projects should be jointly funded by the public and private sectors. It set aside the "aversion" observed by Anadon and Nemet and triggered the first major wave of energy-demonstration projects since the 1980s.[47] But it did not adopt the reforms advanced by Cohen and Noll, Deutch, or others, nor did Congress insist that it do so. Instead, DOE ran these projects, supported mainly by the American Recovery and Reinvestment Act (ARRA), the stimulus package enacted in 2009 in the midst of the Great Recession. These projects provide an opportunity to explore whether the design principles articulated above, which were drawn from prior waves of energy-demonstration projects at home, as well as experience abroad, were put into practice, and what we might learn from this recent domestic experience. We begin with an overview of the portfolio before turning to the policy and management issues.

The Obama-Era Portfolio

In developing the database for this paper, we sought at first to rely on the literature discussed in the previous section. However, there is no consensus on how to operationalize the concept of demonstration. Deutch, for instance, limits the definition to mega-projects costing hundreds of millions of dollars or more.[48] Definitions built around other project characteristics, such as the functions that projects perform, are more typical. For example, the International Energy Agency defines a demonstration project as a plant that can be operated continuously over an extended period of time, demonstrates the entire production process, and is embedded in a value chain.[49]

Given the lack of a consensus definition and the difficulty of assessing such functional characteristics of projects, we took a more pragmatic approach to identifying the Obama-era energy-demonstration portfolio. We searched DOE's website before the end of the Obama Administration for projects that were labeled as demonstrations by the department and initiated in 2009 or later.[50] Programmatically, these projects are overseen by DOE's applied energy offices. They are more mature than those supported by the Advanced Research Projects Agency–Energy (ARPA-E), which are "too early for private-sector investment," and less mature than those funded by the DOE's Loan Program Office (LPO), which funds "initial commercial deployment," such as the ill-fated loan to Solyndra.[51] (See figure 4.)

Figure 4: DOE RDD&D Pipeline[52]



Our approach yielded a portfolio of 53 projects, which are summarized in table 1. (The full database is available as an appendix on the ITIF website.) The projects the technology fields of advanced clean coal (carbon capture, utilization, and storage (CCUS) for power), bioenergy, energy storage, enhanced geothermal energy, FutureGen 2.0 (a single CCUS for power megaproject), industrial CCUS, offshore wind, and smart grid. The total planned budgets for the 53 projects for which data are available range from as low as $1.4 million to more than $4 billion. The planned federal contributions range from less than $1 million to more than $1 billion, with a median of about $12.5 million and an average of $80 million. The federal share of the budget for the median project was 50 percent, with the federal share for well over half of all projects falling between 45 and 50 percent.

Most of the projects in the database were begun in 2010, and none were started after 2011. Slightly more than half (28) were completed by June 2017. Fourteen, including many of the largest projects, as discussed below, were withdrawn before they were completed, so their full budgets were never spent. (ITIF was not able to assemble a full and reliable accounting of actual federal spending, unfortunately.) Another 11 projects were officially listed as active in June 2017, although several of these were expected by industry insiders to be withdrawn before completion.

Table 1: Summary statistics for the Obama DOE demonstration-project portfolio

Technology Field	No. of Projects	Average Project Total Budget (Millions)	Average Federal Project Share	Median Federal Project Share	Total DOE Funding Allocated (Millions)
Advanced Clean Coal	6	$1,412.5	28.8%	26.0%	$1,753.8
Bioenergy	2	$93.6	45.4%	N/A	$85.4
Enhanced Geothermal	2	$28.5	43.4%	N/A	$26.5
Energy Storage	16	$40.5	43.6%	47.9%	$156.6
FutureGen 2.0	1	$1,774.8	59.1%	59.1%	$1,048.3
Industrial CCS	3	$358.1	64.7%	65.9%	$686.8
Offshore Wind	7	$14.5	64.4%	58.2%	$61.2
Smart Grid	16	$53.4	49.1%	49.9%	$422.9
Total	*53*	*$248.5*	*47.9%*	*49.9%*	*$4,241.50*

One striking feature of the portfolio is the absence of nuclear power projects. All of the DOE applied energy offices, [Electricity (OE), Energy Efficiency and Renewable Energy (EERE), and Fossil Energy (FE)], except for the Office of Nuclear Energy (NE), participated in managing this portfolio. Many energy experts argue that nuclear power will be critical to the achievement of carbon-emissions reduction goals. In particular, smaller, more flexible designs than are currently deployed are likely to be required if nuclear reactors are to be integrated into the more distributed and interactive "smart grid" of the future. [53] While the LPO has guaranteed loans for two new reactors that implement incremental improvements in existing designs and NE has supported applied R&D, no advanced design has gathered sufficient technical and political momentum in the United

States to warrant the investment of the billion dollars or more that would be required to demonstrate it.[54]

Renewables, with the exception of offshore wind, are also absent from the list. To some extent, this absence reflects the relatively low capital costs in this field and greater maturity of many key technologies, which means that demonstration projects are less necessary than in other technology fields.[55] The inclusion of seven offshore-wind demonstration projects on the list is somewhat surprising. This technology is well established in Europe, and its capital costs are lower and more modular than many other electricity-generation technologies. The first commercial offshore-wind project in the United States went into operation off Rhode Island in December 2016. Despite the maturity of the technology, DOE's offshore-wind demonstration program has struggled. Institutional and economic issues, such as permitting and gaining local public support, rather than narrowly technical ones, have derailed several of its projects, highlighting these dimensions of the demonstration challenge.[56]

Three categories—advanced clean coal, industrial CCUS, and FutureGen—account for about five out of every six dollars allocated to energy-demonstration projects during the Obama era.

CCUS projects (advanced clean coal, industrial CCUS, and FutureGen) dominate the portfolio from a fiscal perspective. Combined, these three categories account for about five out of every six dollars allocated to energy-demonstration projects during the Obama era. Given the low cost and widespread use of coal and natural gas for electricity generation and as a feedstock for essential industrial processes, CCUS may well be even more important for the transition to low-carbon energy than nuclear power. Of 10 CCUS demonstration projects initiated under the Obama administration, 3 remain active, including two industrial projects and one power project, Petra Nova (see box 2), which is operational.[57] Of course, that means that the other seven were withdrawn or canceled, including the huge, separately managed FutureGen project (see box 1). In addition, none of the projects sought to demonstrate CCUS for natural gas-fired power plants, which faces a somewhat different set of challenges than for coal or industrial processes.[58] Nonetheless, MIT's Herzog rates the United States' CCUS demonstration program as the most successful in the world.[59]

The bioenergy technology field, represented by two projects in table 1, is driven largely by the Renewable Fuel Standard (RFS). RFS was established in 2007 and requires a specific volume of biofuels to be blended into transportation fuels sold in the United States. Innovation for biofuels seeks to replace food crops like corn with alternative feedstocks and to reduce carbon emissions in their production. DOE's Bioenergy Technologies Office (BETO) defines demonstration projects as between one-fiftieth and one-tenth of the scale required to prove economical production at commercial volumes and notes that such projects "have shown greater success when the basic technology principles were already proven at [pilot scale]." The results from demonstration projects, in turn, feed into commercial-scale "pioneer" projects, as called for by the "coordinated sequential approach" referenced above. Both of the projects included here, Myriant's bio-succinic acid plant and Sapphire's algal biorefinery, were initiated in 2010 and completed in 2015; however, neither technology has yet moved to commercial scale due to unfavorable economics.[60]

Finally, more than half of the projects in the portfolio are in the energy storage and smart-grid technology fields, although allocations for these projects account for only about one in every seven dollars of the total. Energy storage projects tackle the critical emerging challenge of integrating much larger quantities of variable and distributed resources into the power system. Smart-grid projects also support the response to the challenge of variable generation as well as pursue a wider array of emerging opportunities to apply information technology more fully in the electricity sector. Some scholars have argued that energy supply options have dominated public-energy RD&D investment in the past, so it is encouraging to observe the heavy presence of these two fields, which straddle supply and demand, in the portfolio.[61]

Project Selection and Down-Selection

The projects span a variety of DOE programs, each with its own administrative apparatus. In general, however, these programs held open calls for project proposals and specified criteria for evaluating the responses. Most programs applied some combination of four criteria: technical merit, projected impact, project plan, and project team. The technical merit criterion incorporated readiness attributes. In the case of advanced clean coal, for example, projects were required to be of "sufficiently large scale to show the potential for market penetration upon successful demonstration" and "integrated with commercial plant operation." The weighting of criteria varied across the programs. The offshore-wind program put a 50 percent weighting on the project plan, for instance, and only 10 percent on the project team, whereas other programs weighted these criteria more equally.[62]

One apparent and important exception to this open and reasonably transparent selection process was FutureGen. (See box 1.) This megaproject, which dates back to 2003 and was terminated for the first time in 2008, was revived through ARRA funding earmarked for its Illinois site. President Obama, then a senator from Illinois, had vowed during his 2008 campaign to support clean coal technologies, and the state of Illinois (which had invested its own funds in the project) and its remaining representatives in Congress (and those of surrounding states) pushed to include it among the "shovel-ready" projects eligible for the stimulus. Much like the Clinch River breeder reactor demonstration project studied by Cohen and Noll, the local fiscal benefits of FutureGen apparently weighed heavily in its vampire-like rise from the dead.[63]

BOX 1: FUTUREGEN CARBON CAPTURE AND SEQUESTRATION PROJECT[64]

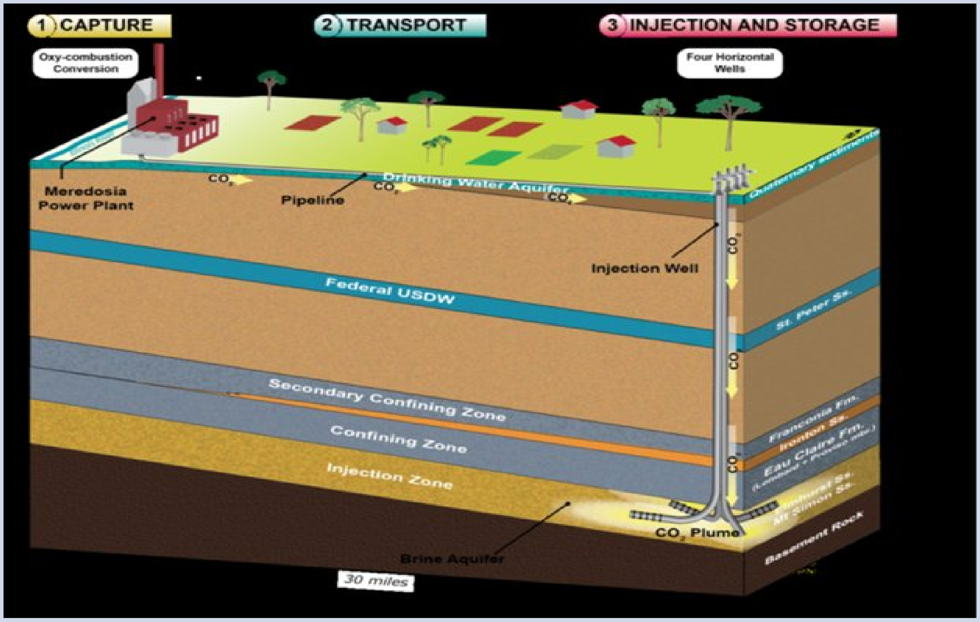
Of the projects in the portfolio reviewed in this paper, the FutureGen Carbon Capture and Sequestration Project most closely resembles the "technology pork barrel" syndrome described by Cohen and Noll in 1991. First proposed by President George W. Bush in February 2003, it survived a near-death experience at the end of the Bush administration and found new life under President Barack Obama before being extinguished for good in 2015. The project was initially budgeted at $950 million, a total that grew to $1.65 billion by the time it was closed out. Approximately $120 million to $130 million was actually spent on FutureGen between 2003 and 2015.

FutureGen 1.0, as the first iteration of the project eventually became known, was quite ambitious technologically. It was intended to demonstrate integrated gasification combined cycle (IGCC) electricity generation, carbon capture and sequestration (CCS), and hydrogen production on the same site. As such, it would have advanced several prongs of the Bush administration's energy strategy simultaneously. The FutureGen Alliance, a nonprofit consortium formed to build the project and to provide approximately a quarter of its costs, was equally ambitious, including some of the biggest coal and electricity companies in the world, not only from the United States, but also China, Australia, and Europe.

The alliance undertook a site-selection process, which was aided by a tax incentive supplied by the state of Illinois. Mattoon, Illinois, was designated as the project's location in December 2007. By then, however, the administration had had second thoughts about the project, due to rapidly escalating cost projections. Amid public conflict, DOE withdrew from the FutureGen partnership and declined to proceed further in 2008. Illinois Governor Rod Blagojevich cried foul, while then-Senator Obama, in the midst of his first presidential campaign, pledged his support to revive the project.

The 2009 American Recovery and Reconstruction Act (ARRA), with its emphasis on clean energy and green jobs, provided the Obama administration with the opportunity to create FutureGen 2.0, which was announced in August 2010. The new version retained the sequestration component of FutureGen 1.0 in Mattoon, but called for retrofitting an existing coal plant in nearby Meredosia, Illinois, with oxy-combustion technology for carbon capture, rather than building a new IGCC plant. This decision lowered the technological risk of the project considerably. (See figure 5.)

Figure 5: Conceptual design of the FutureGen 2.0 Project.[65]



Nonetheless, problems continued to plague FutureGen. In October 2011, facing low-price competition from gas-powered generation, the owner of the Meredosia plant announced that it would close, prompting the alliance to purchase the property and take over the generation component of the project. More difficulties arose in obtaining a permit for sequestering carbon dioxide underground from the EPA, obtaining the land easement for the pipeline to transport carbon dioxide to the sequestration site, and securing private financing to complete major construction. Decision-making delays at DOE headquarters slowed progress considerably as well.

FutureGen 2.0's managers surmounted many of these hurdles as preliminary designs were prepared. DOE, for its part, approved phase 2 of the project (which was to include final permitting and design activities) in February 2013, released a final Environmental Impact Statement in October 2013, and issued a Record of Decision in January 2014. Nonetheless, the agency faced a deadline of September 30, 2015, to expend all federal funds on the project under ARRA. It ultimately decided not to proceed with construction, rather than put the project on a truly impossible timeline or return to Congress to request schedule and budget relief, despite entreaties from members of Congress from Illinois and nearby states.

That said, FutureGen was ultimately terminated again in 2015, and the administration and Congress resisted political pressure to resurrect it. ARRA's requirement that all stimulus funds be expended by September 30, 2015, was a key factor in FutureGen's demise.[66] Other DOE demonstration programs also were able to down-select projects that were moving too slowly or unable to hit specified milestones. Very large CCUS projects, in addition to FutureGen, such as the planned $4 billion Hydrogen Energy California and $1.7 billion Texas Clean Energy projects (both of which were to have received more than $400 million in DOE funding), were among those cut off.

Down-selection processes across these programs vary in their transparency. The bioenergy program is exemplary. BETO convenes an independent panel of experts on a biennial basis to assess each of its projects and reports these assessments to the public. Its 2015 peer review of demonstration projects, for instance, involved six external experts who scored projects on specific criteria and provided an analysis of the overall program. They argued, for instance, that the program should be expanded to include projects "that produce a higher-value non-fuel primary product."[67]

This brief review suggests that the pork-barrel logic laid out by Cohen and Noll did not operate in a deterministic fashion under the Obama administration. For the most part, DOE seems to have been able to insulate its go/no-go decisions from political influence and to carry out no-go decisions at key points in project development. The time limit for expenditure of ARRA funds, backed up by fiscal conservatism in Congress after the Republicans won control of the House in 2010, provided an important assist.

Cost Sharing

All of the projects in the Obama administration clean-energy demonstration portfolio were cost-shared with private partners. Some of the largest projects had the smallest planned federal cost-share. The lowest was 7 percent ($25 million out of more than $350 million) for the Advanced Underground Compressed Air Energy Storage project that was proposed by the California utility Pacific Gas & Electric, followed by a 10 percent federal share for the more than $4 billion planned budget of the Hydrogen Energy California project. (Both of these projects apparently have been discontinued, although no formal announcement has been made, and DOE still lists them as active.) The three industrial CCUS projects, which are also quite large, ranging from $200 million to $500 million in total, lie at the other end of the cost-share distribution. They received federal investments amounting to 60 to 70 percent of each project's total.

Go/no-go decisions have been mostly insulated from political influence. The time limit for spending ARRA funds, backed by fiscal conservatism in Congress after the Republicans won control of the House in 2010, provided an important assist.

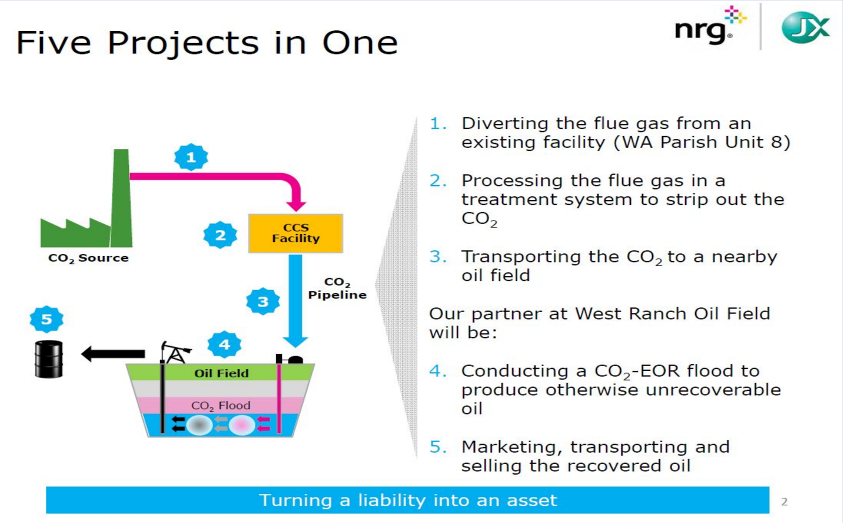
In most cases, the proportion of costs covered by the public and private investors appears to have been set by statutory guidelines, rather than a systematic effort to allocate them according to the benefits that each sector might reasonably expect to receive from a project. Section 988 of the Energy Policy Act of 2005, which authorizes several of the programs reviewed here, specifies that nonfederal partners must contribute at least 50 percent of the estimated costs for demonstration projects. Although the law permits the secretary of energy to grant exceptions to this rule if "technological risk" warrants it, the clustering of the federal share of a majority of projects in the portfolio at around 50 percent suggests that this discretion was not regularly exercised.[68] The industrial CCUS program is authorized to provide up to 70 percent federal cost-share, which accounts for the larger federal role in these projects.

The Petra Nova CCUS project, which at 17 percent received the third lowest federal cost-share, reinforces this observation. The initial proposal that DOE accepted called for capturing carbon dioxide from a 60 MW plant and would have provided a federal cost-share of about 50 percent. After conducting detailed engineering studies, NRG, the main private partner, concluded that a more ambitious project would make more economic sense. It brought in Japanese quasi-government entities as new investors to cover the expansion. "NRG quadrupled the size of the project at no additional cost to the tax payer," DOE Assistant Secretary Chris Smith told researcher Jesse Jenkins, which brought the federal cost-share down to its eventual low level.[69] (See box 2.)

BOX 2: PETRA NOVA CARBON CAPTURE, UTILIZATION, AND SEQUESTRATION PROJECT

NRG's W.A. Parish generating station outside of Houston, Texas, was America's largest independent producer of electricity in 2008, burning up to 30,000 tons of coal per day in four units, with a combined output capacity of 2,475 MW, complemented by 1,270 MW of natural gas-fired capacity.[70] NRG recognized a "significant commercial opportunity" in applying carbon capture technology to the plant in 2007.[71] This gas, which was in short supply in nearby oil fields, was to be sold for enhanced oil recovery (EOR), strengthening the project's economic viability. (See figure 6.)

Figure 6: Petra Nova Project Overview[72]



Five Projects in One

1. Diverting the flue gas from an existing facility (WA Parish Unit 8)
2. Processing the flue gas in a treatment system to strip out the CO$_2$
3. Transporting the CO$_2$ to a nearby oil field

Our partner at West Ranch Oil Field will be:

4. Conducting a CO$_2$-EOR flood to produce otherwise unrecoverable oil
5. Marketing, transporting and selling the recovered oil

Turning a liability into an asset

2

In 2009, NRG fashioned a proposal for the project that aimed to sequester 375,000 tons of carbon dioxide per year for DOE's Clean Coal Power Initiative (CCPI), round three of which had been funded by the American Recovery and Reinvestment Act that year.[73] DOE awarded the project $167 million in 2010, which was intended to cover 50 percent of its costs. Front End Engineering Design (FEED), a process meant to generate detailed cost estimates that were within 10 percent of the final total, was completed later that year.[74]

NRG's analysis led it to reformulate the project and scale it up. The key step was vertical integration of EOR. NRG bought a stake in the West Ranch oil field in Jackson County, Texas, into which the captured carbon dioxide was to be injected. For this process to work, both physically and financially, NRG found that it needed to capture much more of the gas from the power plant's slipstream.[75] It settled on an annual capture rate of 1.6 million tons, quadrupling the project's size.[76]

The new design increased the project's cost to more than $1 billion, but rather than request more funding from DOE, NRG brought on new partners. In addition to $300 million of its own money and the DOE's eventual investment of $190 million, NRG secured $300 million from JX Nippon Equity, $175 million from the Japanese Bank for International Cooperation, and $75 million from Mizuho Bank insured by Nippon Export and

Investment Insurance, the Japanese government's equivalent of the U.S. Export-Import Bank. These entities' interest was undoubtedly drawn by the project's use of Mitsubishi carbon-capture technology and its hiring of Mitsubishi for construction.[77] The project also benefited from a variety of incentives from the state of Texas.

In January 2017, Petra Nova began operation on time and on budget. It is capturing 90 percent of the carbon dioxide emitted by one of W.A. Parish's four coal-fired units. The carbon dioxide is piped 82 miles and used to boost the output of the West Ranch oil field from 300 to 15,000 barrels per day. This field has approximately 10 years of storage capacity. The University of Texas' Bureau of Economic Geology is monitoring the project to ensure that the carbon is fully sequestered.[78]

As far as ITIF could determine, only the Smart Grid Demonstration Program sought to develop a formal cost-benefit framework that might have been used to assign more appropriate cost-shares. The Electric Power Research Institute (EPRI) released a 24-step framework for cost-benefit analysis of smart-grid demonstration projects in 2010, which has been revised twice since, most recently in 2015.[79] However, such methods are very difficult to apply prospectively. A more flexible, negotiation-based approach to establishing the federal cost-share, using the discretion provided to the secretary, might have been a more realistic way to operationalize our second design principle.

Partners

As noted above, the qualifications and composition of the project team were among the criteria applied by DOE to proposals in demonstration-project competitions. The funding opportunity announcements (FOAs) specified, as one might expect, that the project team had to be able to "successfully provide the skills and resources needed to implement the project as proposed," as the FOA for the Clean Coal Power Initiative Round Three put it. This ability was to be assessed in large part based on the team's "background and experience … as evidenced by corporate history of successful completion of similar projects."[80] The criteria also included, depending on the program, commercialization, technology transfer, and/or cost reduction. The skills and resources required to satisfy these criteria should therefore have been integral to each project team's composition.

In the Obama-era portfolio of cost-shared clean-energy demonstration projects, the end user, usually an electric utility, was the most common type of lead partner. End users led slightly more than half of the projects in our database. That makes sense because, in most cases, the services being demonstrated were for power generation or management, and the utility would ultimately be responsible for using the technology to make money. For instance, Duke Energy was the primary partner for the $43 million Notrees Wind Storage Demonstration Project in Goldsmith, Texas, which was built to optimize energy delivery from an adjacent 153 MW wind farm. It also provides frequency regulation services to the ERCOT (Texas wholesale electricity) market. Duke's project team also included a storage vendor (which was eventually replaced) and an electronics, integration, and operations provider, in other words, a team that could replicate the demonstration on a commercial basis.[81] In the case of the planned $125 million Advanced Compressed Air Energy Storage project in Reading, New York, the lead utility, New York State Electric and Gas Corporation (NYSEG), discontinued the project when it became clear that it would not be economical to operate it on a commercial basis.[82]

Technology vendors of various types comprise the next largest group of lead partners, accounting for about a quarter of the portfolio. They were particularly well represented in the energy storage demonstration program. These firms have a stronger incentive than the end user to sustain government funding for projects that are not performing well, since their businesses are generally more dependent on these projects. Project developers, which led roughly another eighth of the projects, have similar incentives. Five of the projects were led by nonprofit entities. The Battelle Memorial Institute, for instance, led the nearly $200 million Pacific Northwest Smart Grid Demonstration Project, which was the largest in the smart-grid program. It used a transactive system to reduce peak electricity loads and system costs while integrating intermittent distributed resources.[83]

The FutureGen Alliance was a unique entity that does not fit comfortably into any of these categories. Many of the biggest multinational coal and electricity firms in the world formed a nonprofit consortium to carry out the project. The consortium members had an interest in seeing CCUS technology demonstrated, but some, such as coal-mining firms, were not directly in the project's value chain. On the other hand, not all of the utilities that would have been responsible for selling the project's power output joined the alliance. Exelon, a major utility in Illinois, where the project was to be sited, eventually did, but Commonwealth Edison (ComEd), another Illinois utility, did not. When the state regulator sought to require these utilities to procure power from the project for 20 years, ComEd announced that it would challenge the ruling, which might have imposed substantial costs on it. Although this decision was not the most significant factor precipitating the project's demise, the challenges of economical production might have been addressed earlier had both affected utilities played larger roles in the alliance.

The Obama DOE imperfectly satisfied the design principle regarding demonstration project partnerships. In many cases, the teams were well suited to the task, but in some, partners essential to the commercial success of the technology seemed to play too weak a role in project execution. In others, the user voice may not have been represented strongly enough to drive innovation toward commercial utility.

Information Sharing

DOE's programs vary in their treatment of technical and performance data generated by demonstration projects. Formally, DOE holds unlimited rights to these data. In practice, this authority is used by some programs to make project data widely available, while others allow the project teams to restrict access.

DOE's Geothermal Technologies Office within EERE provides open access. It created a repository in 2012 to store all data collected from the projects it funds. These data are made available for free, along with a range of other geothermal research resources, to academic and industrial researchers. The ARRA-funded AltaRock Enhanced Geothermal System demonstration project at Newberry Volcano in Oregon, for instance, shared seismic data confirming the creation of an underground reservoir that is the project's heat source. Such validation is essential if the system is to be replicated at other locations.[84]

The smart-grid and energy-storage demonstration programs, which were also funded by ARRA, were subject to detailed reporting requirements. Each project submitted an interim and final performance report that describes the technologies and systems used, summarizes their physical and financial performance, and explains the methodology for making these assessments. These documents are publicly available along with a variety of topical reports and case studies.[85]

In many cases, project teams were well suited to the task, but in some, partners essential to the commercial success of the technology seemed to play too weak a role. In others, the user voice may not have been represented strongly enough.

Other programs provide for greater proprietary control of project-generated data. Firms participating in the offshore-wind and bioenergy demonstration programs, for example, are permitted to withhold technical data from public disclosure for five years following the completion of the project.[86] Such provisions encourage firms who fear losing a competitive advantage in technology development to participate in these programs, but at the potential cost of slowing diffusion of key lessons learned from the demonstration.

The CCUS programs also permit project teams to withhold raw data for a limited time period, but "acknowledges that knowledge sharing among various entities is essential in order to commercialize CCUS technologies." It is very thorough in cataloguing and making accessible presentations and progress reports from project teams. In addition, for the utilization and storage components of the system, the program has developed best practice manuals and a national online atlas. These resources include information about institutional as well as technological practices, such as public education and communication.[87]

If, as Nemet and his colleagues argue, learning and broad knowledge dissemination are the most important priorities for clean-energy demonstration projects, the unevenness across the Obama-era programs in this regard is worrisome. The difficulty of finding information generated by demonstration projects in technology fields such as offshore wind and carbon capture could limit their impact.

Environment for Follow-On Investment

The technologies demonstrated by DOE in the Obama era all have the potential to contribute to the low-carbon energy transition. The future of some of them is almost entirely dependent on continuing policy support over the intermediate term, such as tax incentives or carbon pricing, which is uncertain, while others may be able to attract follow-on investment from commercial interests without such policies.

Smart-grid technologies are prominent among the latter group. The application of information technologies to the operations of the power sector is likely to yield efficiencies and diversify the sector's service offerings, just as it has in many other economic sectors.

Assuming that demonstration projects are able to address the coordination and institutional challenges raised by these technologies adequately, the business case for follow-on investments will presumably be strong.[88]

The costs of technologies such as energy storage and offshore wind must decline further before the business case for follow-on investment will become as compelling as it appears to be for many smart-grid technologies. Demonstration projects in these areas will go some distance toward this goal, but these technologies may well be confined to niche applications unless the market is deliberately sustained by policy measures, such as regulatory mandates and tax incentives, so that they can travel further down the experience curve. In energy storage, states such as California and Massachusetts as well as regional transmission operators such as PJM, are creating a policy environment conducive to follow-on investment.[89] The market for commercial offshore-wind installations is less promising than for energy storage, but the continued expansion of the global market for this technology may improve its domestic prospects over time, even if domestic policy support is relatively weak.

Follow-on investment in CCUS, both for power and industry, is more directly dependent on domestic policies that aim to reduce carbon pollution than other technologies. No matter how much CCUS technologies improve, they will be costlier than running power plants and factories without them, unless the uses provide income that compensates for the costs imposed. The Obama administration's efforts to impose a carbon price through cap-and-trade legislation failed, and its regulatory mandates are likely to be dismantled, which means that there is unlikely to be much follow-on investment in the intermediate term for CCUS technologies now being demonstrated, at least in the United States.[90]

If learning and broad knowledge dissemination are the most important priorities for clean-energy demonstration projects, the unevenness across the Obama-era programs is worrisome.

Bioenergy is similarly dependent on supportive policies to catalyze follow-on investment, although the stance of the Trump administration toward key policies in this area, such as the Renewable Fuel Standard, is less clear than in the case of carbon emissions. As DOE's Bioenergy Technologies Office forthrightly put it, "bioenergy technology may continue to require policy support and regulatory mandates in order to enable the new bioenergy sector while it is being established."[91]

If Hillary Clinton had won the 2016 presidential election, while Congress remained in Republican hands, the prospects for a supportive federal policy environment for follow-on investments in those technologies where it appears to be essential may have been only marginally better than it is now. With regard to CCUS, for instance, neither candidate called for a carbon price to be imposed, and even in the unlikely event that the Clean Power Plan is implemented, it is not by itself stringent enough to make plants with CCUS commercially viable.[92] Nonetheless, it was not unreasonable to have forecast in 2009 that clean-energy demonstration projects begun by the Obama administration would mature in a supportive policy environment. As our literature review showed, handicapping the future of energy markets and policy over a 5- or 10-year time horizon, particularly in a highly polarized polity, is extremely hazardous.

ENERGY DEMONSTRATION POLICY: FROM THE PAST TO THE FUTURE

Energy demonstration projects are expensive, difficult, and prone to failure. A 100 percent success rate for such projects would indicate a flawed selection process that took too little risk and simply substituted public capital for private. Some failures, though, are worse than others. Challenges in design, construction, or operation that were tackled in good faith, but proved harder than anticipated to solve, are easier to swallow than projects that drift on, even though everyone knows that they do not have a prayer of leading to commercialization.

The conventional wisdom about the demonstration projects that the United States undertook in the 1970s and 1980s is that they were mostly the bad kind of failure. This interpretation was somewhat unfair to the policymakers of that era, especially in light of the dramatic and unanticipated fall in energy prices. The experience of the Obama era calls for a more nuanced interpretation. DOE was able to limit its losses in cases of failure, even on the biggest projects that should have been prone to the pork-barrel dynamics described by Cohen and Noll. DOE scored some apparent successes as well, although it is too soon to issue a final judgment in this regard. Many of these successes were modest in scale, but the list includes some projects in the nine-figure range, with Petra Nova pushing the billion-dollar mark.

The conventional wisdom about the demonstration projects of the 1970s and 1980s is that they were mostly the bad kind of failure. This was somewhat unfair, especially in light of the dramatic and unanticipated fall in energy prices. The experience of the Obama era calls for a more nuanced interpretation.

Yet, as the previous section shows, it cannot be said that the Obama DOE's management of demonstration projects conformed fully to the best practices identified by scholars. Significant further improvement should be made when the next wave of demonstrations goes forward. Whether the best way to make such progress is by creating a new institution to take DOE's place, as called for by Deutch and others (including the author in prior work), is a difficult conundrum. (See box 3.) The case for change, based on the analysis in this paper, is less compelling than it was before the Obama administration, and barriers to standing up something new and more effective than DOE have risen.

BOX 3: PROPOSED ALTERNATIVES FOR SELECTING AND MANAGING ENERGY DEMONSTRATION PROJECTS

DOE's discouraging track record in selecting and managing energy-demonstration projects has prompted numerous proposals to create new institutions to take over these roles. Two of the most prominent are:

Energy Technology Corporation (ETC). John Deutch has advocated establishing an independent, government-chartered corporation with the sole purpose of supporting large-scale energy demonstration projects. Unlike DOE, the ETC would have the flexibility to hire and fire personnel and to negotiate and oversee contracts, loans, and other funding instruments according to commercial practices. It would be governed by a board of directors nominated by the president and confirmed by the Senate. The ETC would receive a one-time infusion of funds to get started, but otherwise be immune from the annual appropriations cycle that hamstrings federal energy demonstration decision-making.

Deutch's 2011 formulation recommended that the proposed ETC receive $60 billion that could be spread over approximately 20 projects over 10 years.[93]

Regional Innovation Demonstration Funds (RIDFs). Richard Lester and the author of this paper have proposed a regional mechanism for selecting and managing demonstration projects that would sidestep the pitfalls of federal policy-making. RIDFs would rely mainly on state public benefit charges, regional cap and trade program revenues, and other nonfederal sources for their revenues, although federal matching funds might also be provided. As the name suggests, groups of states would work together in these institutions, which could then specialize in projects to develop energy resources of particular interest to each region, such as offshore wind on the coasts or concentrating solar power in the desert southwest. The federal government would play a vital but limited role in this scheme by serving as an expert "gatekeeper" to qualify projects across the nation for RIDFs support, limiting the risk of favoritism.[94]

Moving forward, clean-energy technology demonstration policy should reflect the following recommendations and findings.

- The United States should build and sustain a robust, diverse portfolio of technology-demonstration projects as part of a comprehensive and strategic clean-energy innovation policy that links backward to R&D and forward to market development. With the expiration of the stimulus package and the completion (or withdrawal) of Obama-era projects, the demonstration component of the portfolio is not robust or diverse, and it is rapidly dwindling.

- The federal government should continue to co-invest with private partners in clean-energy demonstration projects. The high technical and market risk, long duration, and inability to fully appropriate the benefits (including societal benefits) of such projects deter private investors. There is no other public investor with as broad an interest in capturing the societal benefits of such projects and deep enough pockets to fund them besides the federal government. The 2009 stimulus package, which funded the latest round of projects, was a good investment mechanism because it imposed a sunset date on project completion and did not require annual appropriations.

- Private-sector partners, especially technology end users, should continue to take leadership roles in implementing clean-energy demonstration projects. The operational experience gained by these partners is a key benefit that motivates their investment in the demonstration and enables full commercialization of the technology after it has been demonstrated. The Obama period is encouraging in this regard. A wide array of private collaborators stepped forward to develop and participate in demonstration projects, including many end users, such as electric utilities in the case of power plants and grid projects.

- Federal cost-sharing for demonstration projects should become more flexible in order to accommodate varying risk profiles. Cost-sharing ratios in the past have clustered around arbitrary levels established by Congress, rather than reflecting the actual allocation of risk. In the case of programs authorized by the Energy Policy Act of 2005, the secretary of energy should exercise the discretion allowed for in that legislation to negotiate more appropriate cost-shares. In other cases, Congress may need to delegate such discretion.

- Federally funded clean-energy demonstration projects should make information sharing among all potential users of the demonstrated technology a higher priority than it has been in the past. Although such information sharing may reduce the incentive for private partners to invest in demonstrations, it accelerates diffusion and enhances competition as the technology is being commercialized. Government-wide guidelines that mandate an open-data approach would overcome the inconsistency in this regard that is evident in the projects reviewed here. Program-evaluation metrics should include information-sharing and learning criteria along with more conventional cost and performance data. A more flexible approach to cost-sharing would also enable information sharing by allowing the federal government to compensate private project partners for any loss of a competitive edge caused by open-data requirements.

Initial selection of clean-energy demonstration projects should avoid excessively rapid scale-up of unproven technologies. Different kinds of problems must be solved at each stage; skipping stages rarely works out, as recent CCUS projects suggest.

- Initial selection of clean-energy demonstration projects should avoid excessively rapid scale-up of unproven technologies. Different kinds of problems must be solved at each stage of scale-up; skipping stages rarely works out, as recent CCUS projects suggest. Similarly, project selection should not incorporate overly optimistic assumptions about the economic and policy environment for follow-on investments. Some projects in the demonstration portfolio analyzed here, such as the very large compressed air energy storage projects, may have been selected with rose-colored glasses on. That said, energy markets and technologies are unpredictable and prone to surprise, so there will always be room for disagreement about what the environment is likely to be 5 or 10 years after a project is initiated.

- Federal policymakers, including members of Congress, should expect that some demonstration projects will be unsuccessful and should be prepared to terminate them when they fail to meet major milestones. The experience of the past decade suggests that the "technology pork-barrel" syndrome that plagued an earlier generation of projects, in which unsuccessful projects lived on because they provided local economic benefits, is not inevitable. It is possible, however, that this progress was the result of a confluence of temporary forces, including the design of the stimulus package, congressional hostility toward the president after 2010, and fiscal austerity. Future appropriations for clean-energy demonstration projects should be explicit about the milestones that such projects are expected to meet. Congress should examine publicly and carefully whether these milestones have been achieved before approving follow-on investments.

- A continuing effort should be made to explore the viability of establishing alternatives to DOE for managing federal investment in clean-energy demonstration projects, such as the proposed Energy Technology Corporation and Regional Innovation Demonstration Funds (see box 3). Even though Petra Nova shows that DOE has the capacity to select and invest in a successful large-scale demonstration project and FutureGen, similarly, shows that it can pull the plug on one, the circumstances in both cases were unusual. The creation of one or more alternatives would not necessarily spell the end of DOE engagement in demonstration projects; the new mechanism might only handle projects with very specific attributes, such as extremely large-scale projects in the case of the proposed Energy Technology Corporation, while leaving the remainder of the portfolio to DOE.

- Federal agencies other than DOE, such as the Departments of Defense and Transportation, should consider co-investment in clean-energy demonstration projects when such investments are consistent with their missions. Regions and states should be engaged as active partners in federally funded projects and should consider taking leadership roles if federal co-investments are not forthcoming. Diversity across regional energy systems is a strength of the U.S. system that could be leveraged for the benefit of the nation as a whole.

As each year passes, the urgency of carrying out low-carbon energy demonstration projects grows. Successful demonstrations may take years or even decades for their impact to be fully felt, as they slowly reshape long-lived infrastructure such as power plants and electrical grids. The 2050 endpoint of the Paris Climate Agreement is only a bit more than three decades away. Failure to sustain the momentum created in the early 2010s may well be more profound than any failure to learn the right lessons from that experience.

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ACKNOWLEDGMENTS

ITIF staff member John Wu and George Mason University student Timothy Bullock provided vital research support for this paper. The author thanks Rob Atkinson, Jesse Jenkins, Greg Nemet, Chris Smith, and David Victor for providing insights, comments and suggestions. Any errors or omissions are the author's alone.

ABOUT THE AUTHOR

David M. Hart is a senior fellow at ITIF and director of the Center Science, Technology, and Innovation Policy at George Mason University's Schar School of Policy and Government, where he is professor of public policy. He is also a member of ITIF's board of directors. Hart is coauthor (with Richard K. Lester) of Unlocking Energy Innovation (MIT Press).

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