ARPA-E: Versatile Catalyst for U.S. Energy Innovation

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The innovation resources of the United States are vast. The nation is blessed with extraordinary human capital, dynamic companies, creative research institutions, and great wealth. Its legal and institutional frameworks have enabled the launching of some of the world's most important industries in recent decades. But in energy, including next-generation non-fossil-fuel energy, one of the defining sectors of the 21st century, this country's innovation achievements have fallen far short of their potential. Institutional innovation is required to unlock this potential and usher in an era of better and cheaper energy.[1]

The Advanced Research Projects Agency – Energy (ARPA-E) is an important new institution that has begun to demonstrate its value as a versatile catalyst of energy innovation. Created by Congress in 2007, and funded for the first time in 2009, ARPA-E more effectively generates new ideas that are useful to energy innovators than its older brethren in the federal R&D establishment, and it bridges the gap between research and use in ways that these other agencies simply do not. As of February 2017, for instance, 580 ARPA-E project teams, which received a total of approximately $1.5 billion from the agency, had formed 56 new companies and raised more than $1.8 billion in private-sector follow-on funding to continue to advance new technology toward the market.[2]

These results warrant sustaining and expanding ARPA-E and infusing some of the practices that have made it so effective into other federal R&D funding agencies. Yet, the Trump administration has proposed to shut it down instead, on the grounds that "the private sector is better positioned to finance energy R&D and to commercialize innovative technologies."[3] Although the Senate Energy and Water Appropriations Subcommittee "definitively rejected this short-sighted proposal" and appears poised to save ARPA-E from the budget axe in fiscal 2018, the fact that such a rescue was necessary suggests that ARPA-E's approach and its achievements deserve to be better understood beyond the boundaries of the technical communities with which it works on a daily basis.[4]

Firms funded by ARPA-E raise more private capital than other clean energy startup firms and have particularly high odds of being in the top 10 percent of the fundraising distribution.

This report explains why ARPA-E is needed, what it does, and how it has helped the nation make progress toward important goals. We rely heavily on research done by others, particularly the recent National Academies' *Assessment of ARPA-E*. We also bring new evidence to the table to refute the claim made by the administration and its allies that the private sector would step in to support ARPA-E projects if the agency were to be zeroed out. Our analysis of early stage private investment in clean energy startups shows that this claim is inaccurate. The data support statements made by project leaders and analysts, such as the Government Accountability Office as well as the Academies' committee, that ARPA-E funding complements, rather than crowds out, private funding.[5] In particular, we show that firms funded by ARPA-E raise more private capital than other clean energy startup firms and have particularly high odds of being in the top 10 percent of the fundraising distribution. We argue that ARPA-E funding helps firms become much better candidates for follow-on private support. Cutting ARPA-E would impede the unlocking of the nation's innovation resources to tackle urgent problems of energy supply, management, and use.

We conclude that:

- **ARPA-E's operational autonomy and distinctive operating procedures should be maintained.** Although consultation and collaboration between ARPA-E and the rest of DOE should be encouraged, efforts by DOE headquarters and senior management to exert greater control over ARPA-E should be resisted.
- **ARPA-E's budget should be expanded.** There are many more "white spaces" in energy technology that have not been explored, and the impressive responses to ARPA-E solicitations suggest that there is no shortage of potential innovators.
- **ARPA-E should be reauthorized.** Reauthorization would send a strong signal that ARPA-E's autonomy should be maintained and lay the groundwork for expanding its budget.
- **An ARPA-E trust fund should be established with royalties from oil and gas production on federal lands.** In an era of federal constraint, such a fund would provide stability and certainty for the agency.
- **ARPA-E practices should be infused into the rest of DOE.** Adoption of appropriate elements of the ARPA-E model would improve the performance of DOE's famously byzantine bureaucracy.

This report begins by establishing the need for ARPA-E. It explains briefly why innovation that leads to cheaper, cleaner energy is needed and why neither markets nor the rest of the federal energy innovation support system provide enough of it. We then describe the distinctive operating procedures and culture that ARPA-E has established in its eight years of existence. The final two major sections provide evidence that ARPA-E is working. The first focuses on its ability to support the formulation of novel concepts as expressed in scientific and technical publications and patents. The second focuses on how ARPA-E nurtures ideas to the point where private investors see the potential profit in them and commit their own capital. We analyze investment data to show that ARPA-E complements, rather than substitutes for, private investment. ARPA-E funding allows companies to become good candidates for private investment. We close by elaborating on the recommendations summarized above.

WHY CLEAN ENERGY INNOVATION IS NEEDED AND WHY MARKETS DON'T PROVIDE ENOUGH OF IT

Energy is a massive and complex business. Americans spent more than $1.1 trillion on gasoline, electricity, and other energy products and services in 2015.[6] An enormous infrastructure extracts, processes, and delivers energy, and an even more enormous one uses it. The smooth operation of this infrastructure is essential to daily life. Americans' livelihoods, leisure, and well-being depend on it.

The U.S. energy system provides many benefits. American energy supplies are generally reliable, and most Americans have access to the energy they need. However, energy costs are volatile and have historically risen faster than those of other goods and services.[7] Breaking this pattern and accelerating productivity gains will require fundamentally new kinds of energy generation, distribution, and storage that only technological innovation can provide.

The current energy system also imposes significant costs and risks that are not incorporated into energy prices. The system is not as secure or as resilient as it should be.[8] Despite the increase in domestic oil and gas production in the last decade, the United States still runs a trade deficit in energy.[9] Energy industry workers and communities frequently suffer uncompensated negative health effects.[10] Energy systems often pollute their local environments, and they produce 84 percent of the United States' gross greenhouse-gas emissions that contribute to climate change worldwide.[11]

Innovation is needed to reduce these costs and risks. Energy security and resilience would be enhanced by innovation in the design and operation of energy infrastructure, like electricity transmission and distribution grids, as well as in energy storage. Local health and environmental consequences would be alleviated by innovation in extraction operations and emissions controls. Greenhouse gas emissions would be mitigated by innovation in energy efficiency and low-carbon power generation, among other things.

Economists have long shown that technological innovation does not necessarily respond to market incentives. Underinvestment in ideas, because they sometimes benefit others as well as (or instead of) the original investor, is a classic instance of market failure and an appropriate and widely-accepted justification for government support of scientific research and legal protection of intellectual property. Similarly, pollution reduction is unlikely to be undertaken by firms as markets do not reward it, a rationale that justifies environmental regulation as well investment in environmental R&D, which in turn, may drive innovation in pollution control.[12]

Even if energy markets worked perfectly well, transformational innovation in this field would still be difficult. Restructuring or replacing complex, physical systems, like the electricity grid or the petroleum and natural gas extraction and distribution network, requires solving daunting technical problems that may in turn rest on progress in fundamental science. As these systems become increasingly information-rich cyber-physical systems, these problems become even more difficult. The interdependencies within these complex systems create additional barriers to change.

Energy-sector firms tend to be conservative and sometimes resistant to innovation.

But markets generally don't work very well in the energy sector. Some energy industries, like oil and gas, for instance, are capital-intensive, making them hard for innovators and entrepreneurs to enter. The innovations that firms in such industries do make tend to be incremental and focused on developing and protecting their existing energy businesses, rather than transformational.[13] Other energy industries, like electric power, are subject to price and entry regulation that at best imperfectly simulate market incentives, and at worst strengthen monopoly power through regulatory capture. Innovation in energy efficiency is often impeded by split incentives between energy users and those who pay energy bills (as in the case of renters and landlords) as well as by a lack of information.[14]

For reasons as varied as the markets in which they operate, energy-sector firms tend to be conservative and sometimes resistant to innovation. The International Energy Agency (IEA) has aggregated data on R&D spending as a percentage of sales revenue, a widely used indicator of innovation. The IEA finds that "oil and gas companies and electric utilities, on average, both spend around 0.25 percent of their revenue on R&D each year." Even companies that make the capital equipment that these companies buy from invest only about 2.5 percent of their revenues in R&D, far below the levels achieved in more innovative industrial sectors like semiconductors and pharmaceuticals.[15]

The story behind hydraulic fracturing and horizontal drilling, the key innovations that allow natural gas to be economically extracted from shale formations, support this point, rather than refute it. Only a few maverick firms like Mitchell Energy pursued the technology. Such firms must share credit for opening up this important new energy resource with public-sector institutions. As Michael Shellenberger and his colleagues at the Breakthrough Institute have shown, the federal government funded research in fields like geology and computing that underpinned shale gas innovations, supported demonstration projects, countenanced and funded industry-wide collaboration that might otherwise have drawn antitrust scrutiny, and provided tax breaks for companies developing and deploying the new technology. This public/private innovation process extended over several decades before costs were sufficiently low for shale gas to be competitive with conventional gas.[16]

Energy markets fall far short of the ideal that students learn about in Econ 101. Even if they did not, innovation would still be inadequate. The modest levels of innovation that they support tend to be incremental; transformational innovation typically requires private firms to partner with the public sector in some fashion. If the United States is going to reduce the costs, avert the risks, and expand the benefits of its energy system through innovation, the public sector must play an active role in the process, as it did in the case of shale gas. But the federal government, like the energy markets, is not playing this role as well as it ought to.

GAPS IN THE FEDERAL CLEAN ENERGY INNOVATION SUPPORT SYSTEM THAT ARPA-E HELPS TO FILL

The federal government has a long history of fostering technological advances that contribute to the achievement of national goals. Alexander Hamilton famously called for a manufacturing policy that would free the nation from dependence on Great Britain. Abraham Lincoln established the land-grant university system, with its agricultural and mechanical ("A&M") schools, in order to enhance productivity in both of these broad areas.

Some federal programs that support energy innovation, particularly those associated with natural resource extraction, share this century-old heritage. Most such programs, however, can be traced to the immediate post-World War II period or to the 1970s energy crises, and they carry with them both the strengths and weaknesses of these founding moments. ARPA-E, a 21st century invention, helps to address two key weaknesses that characterize many current federal energy innovation programs: (1) an over-reliance on the conservative peer review method of resource allocation and (2) a reluctance to fund proof of concept and validation projects that bridge the gap between basic research and commercialization.

The years immediately after World War II were pivotal for U.S. science, technology, and innovation policy. The war was won in part due to breakthroughs like radar, synthetic rubber, and the atomic bomb. After the war, policymakers engaged in an intense debate about how best to sustain such progress. Vannevar Bush, who had served as President Franklin D. Roosevelt's science advisor and overseen much of the R&D effort during the war, including the Manhattan Project, took the view that the scientific and technical community performed best when it had a great deal of autonomy. Bush feared that heavy-handed central control would stifle creativity.[17]

Federal agencies like the Office of Naval Research (ONR), the National Institutes of Health (NIH), and the National Science Foundation (NSF), which were founded in this period, were deeply molded by Bush's perspective.[18] Their leaders interpreted his position to mean that these agencies should mainly fund projects proposed by researchers in the priority order determined by their peers. To do otherwise, they argued, would yield second-class science. To distribute research funding by state or according to the preferences of "agricultural and mechanical" users of research, as was the custom in the land-grant system, struck the postwar scientific establishment as archaic.

The Soviet Union's launch of Sputnik in 1957 shocked the United States and prompted a partial rethinking of the peer review model of resource allocation. Sputnik suggested to some policymakers that more of the nation's innovation resources should be deliberately directed toward the achievement of national missions, such as defense and space. The Defense Advanced Research Projects Agency (DARPA), which became the model for ARPA-E, was founded in Sputnik's wake, along with the National Aeronautics and Space Administration (NASA). As MIT's William B. Bonvillian puts it, DARPA practiced "connected science" in which users' goals and the defense mission informed project selection.[19]

The Atomic Energy Commission (AEC) was created in 1946 to carry forward the work of the wartime Manhattan Project. It was, on the one hand, "an island of socialism" that operated a vast industrial complex devoted to producing nuclear weapons.[20] But it was also the patron of atomic physics and a range of other disciplines that the nuclear weapons complex drew upon. In this role, the AEC largely adhered to the peer review model and let the research community set its funding priorities.[21] These priorities included building ever-larger instruments for studying subatomic particles, a pathway that culminated in the ill-fated Superconducting Supercollider (SSC), which went massively over budget and fell far behind schedule before it was killed by Congress in 1993.[22] Although great science might well have been performed with the SSC, the project demonstrated the drift of the Department of Energy (DOE), the AEC's successor agency, away from its original objective of supporting energy innovation.

The SSC setback notwithstanding, DOE's Office of Science (OS), with an annual budget of about $5 billion, carries forward this legacy today. OS is a complex organization that performs a variety of functions and serves as the steward of much of the DOE national laboratory system, but at its core it remains oriented toward advancing fundamental science through peer review. The strength of peer review, as Bush argued, is that it shelters researchers from wasting effort on infeasible programs drafted by poorly-informed non-experts. But this strength has corresponding weaknesses, including a tendency to insularity and conformity, along with a lack of emphasis on meeting national goals or connecting to market opportunities.

The SSC case illustrates the risk of insularity, an inability to recognize constraints imposed upon expert communities by their social environment. Conformity operates more subtly. Peer reviewers tend to reward what has worked in the past. Older, more established grant applicants appeal to their older, more established peers, leaving newcomers and out-of-the-mainstream thinkers at a disadvantage. One indicator of this phenomenon is the rising age of first-time recipients of federal grants. At NIH, for instance, the typical scientist receiving her first standard grant from the agency is more than 42 years old.[23]

The challenge of conformity has been recognized by the policy community. NIH directors created the New Innovator and Early Independence programs in order to improve the odds of first-time applicants. Yet, such efforts are largely marginal in institutions where peer review is so deeply rooted. DARPA, and later ARPA-E, adopted a different principle of resource allocation altogether. As we describe in more detail below, these agencies empowered individual program managers to make funding decisions. Although the program managers must be members of and in touch with their expert communities, they are free to exercise their own idiosyncratic judgments when selecting projects for funding, even if the majority of their peers disagree.

We are not arguing that empowered program managers should displace peer review for all federal research funding decisions, but rather that these approaches are complementary. Peer review sustains the lower-risk, incremental strategies that are essential to the steady progress of what the philosopher Thomas Kuhn labeled "normal science."[24] Empowered program managers often take greater risks, with greater variability in results, but also reap concomitantly greater rewards. DARPA may have made some bad bets over the years, but it famously nurtured such breakthroughs as the Internet, GPS, stealth, virtual reality, driverless cars, automated translation, and battlefield robots among others.[25]

ARPA-E was designed to, and has begun to, fill the gap left by OS's heavy reliance on peer review. It was also designed to, and has begun to, replicate DARPA's capability by helping energy researchers get "connected" to real-world challenges, to use Bonvillian's term. This aspect of ARPA-E's design complements the work of DOE's applied energy offices, which focus on particular energy resources, like renewables, nuclear power, and fossil energy. The applied energy offices together receive about $4 billion in appropriations each year.

DOE was assembled in the wake of the 1973 oil crisis from "a loosely knit amalgamation of energy-related programs scattered throughout the Federal Government," as the agency's own history puts it.[26] The Office of Fossil Energy (known as FE), for example, was extracted from the Bureau of Mines in the Department of Interior, whereas the Office of Nuclear Energy (NE) shared the same Manhattan Project heritage as OS. Despite some attempts to create a more coherent, overarching mission and structure, DOE remains "a loosely knit amalgamation."

The upshot, as David Garman and Samuel Thernstrom have put it, is that "DOE's applied energy efforts are divided into technology-specific silos...that promote technological factionalism rather than focusing on innovations that would meet America's energy needs."[27] This structure can lead to technological cul-de-sacs, unproductive competition, and missed opportunities for cross-cutting and integrative innovation. DOE in this regard resembles DOD before DARPA, which was dominated by the Army, Navy, and Air Force and their parochial land, sea, and air interests. And, like the military services, each of DOE's technology silos has been subject to funding volatility, due to the ups and downs of energy markets, accidents and crises, and changes in partisan control of Congress and the presidency.[28]

Moreover, Garman and Thernstrom continue, "there is no enduring, systematic effort to bridge the gaps between basic research activities and applied technology challenges" within DOE. These gaps yawn particularly wide in the energy sector. Its enormous scale and complexity and the presence of powerful incumbents mean that the energy innovation process is often slow and difficult. Energy innovations must often fit into long-established systems or contribute to entirely new ones being built from the ground up. They typically must meet demanding cost and reliability standards. They sometimes confront deeply-ingrained habits among consumers. If there is no continuity of effort among public innovation organizations to bring an energy technology close to maturity, as we have argued above and will detail below, there are unlikely to be private investors who will be willing to fill this large gap.

ARPA-E's support for proof of concept and validation projects allows ideas that might otherwise have been orphaned to move a large step closer to commercialization. The agency occupies what Donald Stokes labeled "Pasteur's Quadrant." Louis Pasteur drew insights that led to his pioneering germ theory of disease from his industrial experience and he was a practitioner of hands-on experimentation in the field. Stokes distinguished this approach to innovation from that of pure research with no thought of use (which he called "Bohr's Quadrant") and applied experimentation that did not seek more fundamental understanding (which he identified with Edison).[29]

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ARPA-E, which has received about $300 million per year, less than a tenth of the budget of OS or the applied energy offices, aspires to the same combination of exciting science and practical utility that Pasteur achieved. By targeting "Pasteur's Quadrant," the agency plugs key gaps left by the legacy federal energy innovation support system.

HOW ARPA-E WORKS

ARPA-E's origins lie in *Rising Above the Gathering Storm*, a 2005 report of the National Academies. The Academies called for a new agency that "would sponsor creative, out-of-the-box, transformational, generic energy research in those areas where industry by itself cannot or will not undertake such sponsorship, where risks and potential payoffs are high, and where success could provide dramatic benefits for the nation."[30] ARPA-E was authorized in the COMPETES Act of 2007 and received its first appropriation in fiscal year 2009, primarily through the American Recovery and Reinvestment Act. Regular appropriations have been provided by Congress since fiscal year 2011.[31]

In order to take greater risks than peer reviewers might countenance and to focus the attention of the expert community on problems of interest to energy technology users, ARPA-E was endowed with greater autonomy and more flexibility than other DOE grant programs. Four features are particularly distinctive and important: who ARPA-E hires to manage its programs; which areas of science and technology these program managers pursue; how they select projects to be funded; and how they manage these projects post-award.

Like DARPA, ARPA-E seeks to attract outstanding technical experts from outside the government to serve as program managers. They are drawn from industry and academia by the prospect of having a big impact in a short period of time. They are hired for only three years, through a much simpler hiring process than is typical of federal agencies. They are encouraged by the agency's senior management to aim high and think outside of the proverbial box. The program managers lie at the core of a "culture focused on talent, openness, and empowerment that encourages risk taking, and hence a high tolerance for flexibility to learn what does not work on a path producing innovative outcomes," in the words of the National Academies' recent assessment.[32]

The first part of a program director's term is absorbed by designing a research program. This process requires intensive engagement with the energy innovation community to identify a "white space" that has great potential but has been underexplored. Program managers consult with key players in industry, academia, and government over a period of months and organize their own workshops to gather information and set goals. Any prospective program must satisfactorily answer a set of challenging questions about its impact, including the strategy for transition into use and potential nontechnical barriers to that transition (figure 1). The final hurdle is "constructive confrontation," which the agency defines as open debate in a context of professional rapport, involving ARPA-E's senior leaders and the program directors' peers.[33]

Figure 1: Questions That Must Be Answered for New ARPA-E Programs[34]

Program Technical Goals	▸ What is the global landscape of the field—science, technology, markets, players? ▸ If successful, what specifically will the program accomplish technically? ▸ Has the program been coordinated with DOE?
Mission Impact	▸ What impact would this success have on the agency mission when the technology becomes widely used—what's new and why is it a potential game-changer? ▸ How much better will the new technology be than existing technologies along quantitative metrics?
Technical Approach	▸ What are the key technical challenges and what are the ideas for overcoming these barriers?
Transition	▸ What is the transition strategy (risk profile and time horizon)? ▸ What are the non-technical barriers to transition (policy, markets)? Will technology scale in cost and volume? ▸ Who are the customers who will absorb this technology and who will potential players be?
Program Metrics	▸ What are the metrics, milestones, and schedule for this program? ▸ How much will the program cost and why?

A program director's work eventually manifests as a Funding Opportunity Announcement (FOA). The FOA is open to individual companies, universities, national laboratories, nonprofits, and any combination thereof. Most ARPA-E FOAs have elicited strong responses from the community of potential performers. On average, only about one in every ten applicants is selected for an award in these programs, although the ratio varies from program to program.[35]

The program director leads the process of selecting projects. Anna P. Goldstein and Michael Kearney provide a detailed review of the selection process, which involves input from expert reviewers but importantly gives the program director significant discretion in the use of the insights provided by the reviewers. In fact, their careful analysis shows that only about 50 percent of projects that ARPA-E programs fund would have been funded under the traditional peer review process.[36] As a result, program portfolios are more diverse and risky, and they reflect more fully the vision of ARPA-E's managers than traditional peer review programs.

ARPA-E has since 2014 had its own contracting office, which allows the agency to take fuller advantage of its flexibility, particularly in the use of cooperative agreements for the management of awards.[37] This structure provides the program directors with the authority to take a hands-on approach to project management that is consistent with the agency's culture. Program directors meet quarterly with awardees and frequently revise technical tasks and milestones. Each project has a set of go-no-go milestones that, if unmet, will result in the termination of the project. These interactions allow program directors to limit the downside risk in their portfolios. After program directors select a highly uncertain portfolio of projects and engage in active management to strengthen them, they proceed to terminate about 10 percent of them before they are completed.[38]

Additionally, program directors convene all recipients within a program on an annual basis to facilitate the disclosure of findings and the sharing of tacit information. Together, these practices build communities that facilitate the cumulative development of knowledge critical to expanding the intellectual horizons in these technical domains. They also provide certification and signaling functions that are valuable to potential follow-on investors. These practices are similar to those viewed as fundamental to the success of DARPA.[39]

ARPA-E's work helps fill some very important gaps in the energy innovation system and complements the work of other organizations. But it is not a panacea for all that ails the system.

The what, who, and how of ARPA-E add up to a very different set of outputs than those of other federal energy innovation programs. Its projects are best characterized as high-risk, high-impact applied research, a domain largely unexplored elsewhere in DOE, and yet, exceptionally critical for both moving forward the boundaries of science and translating science to impact in the energy system. Although it is too early to pass a final judgment on the results of this institutional innovation, ARPA-E's short history provides promising evidence that its approach is working.

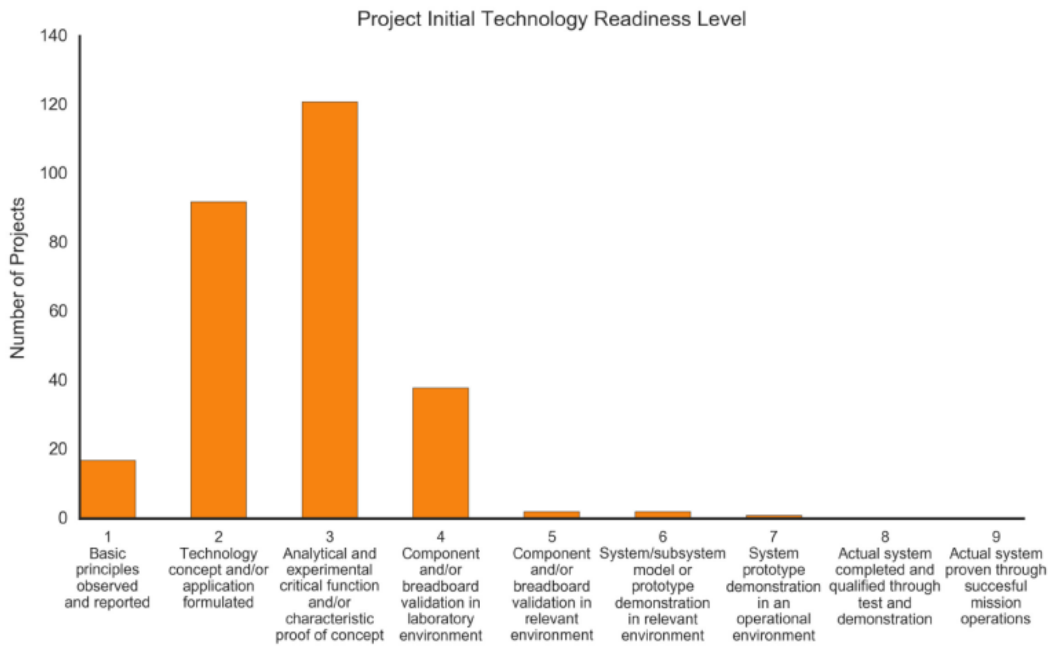
ARPA-E'S PERFORMANCE

ARPA-E 's ultimate mission is to produce technologies that strengthen energy independence, reduce emissions, and improve energy efficiency; and to support U.S. leadership in energy technology. ARPA-E's work helps fill some very important gaps in the energy innovation system and complements the work of other organizations, including other DOE offices, like OS and the applied energy offices. But it is not a panacea for all that ails the system. For example, recent work by ITIF highlights the gap in support for demonstration projects, which is not one that ARPA-E is designed to fill.[40] This context is important to consider in assessing ARPA-E's performance.

To pursue its mission, ARPA-E supports high-risk, high-reward projects across a broad spectrum of organizational contexts, from scientists in academic labs to engineers at startup firms and large companies. These projects span the early and middle phases of what is often a multi-decade innovation process, as illustrated by the story of shale gas. As a result, there is no single performance metric appropriate to every project. Some projects are primarily oriented toward advancing knowledge in light of potential uses, whereas others are focused on turning ideas into potentially marketable services and products.

Figure 2, which is drawn from the National Academies' *Assessment*, categorizes ARPA-E projects using the Technology Readiness Level (TRL) scale. The vast majority of projects fall into TRLs 2 (concept formulation), 3 (proof of concept), and 4 (validation). Although the complexity and long duration of the energy innovation process means that it is not feasible to judge the ultimate impact of these projects on national goals, the TRL scale points us to intermediate markers of success for assessing ARPA-E's performance. In this section, we focus first on indicators of concept formulation, publications and patents. We then turn to indicators of proof of concept and validation, particularly follow-on funding. Although these indicators are imperfect, they strongly suggest that ARPA-E has been a success.

Figure 2: Technology Readiness Level of Projects Funded by ARPA-E[41]



Concept Formulation: Publications and Patents

Scientific and technical publications serve as indicators of the creation of new abstract knowledge. A publication has been certified by the members of a scientific or technical field to be a contribution distinct from the prior literature. The value of any particular publication is indicated in part by the prestige of the journal in which it is published; each field has its own pecking order of journals. The value of a publication is also indicated by citations made to it by later authors. Most publications are never cited, while a few garner a disproportionate number of citations.

For its *Assessment of ARPA-E*, the National Academies' committee gathered publication data through the end of 2015. It found that ARPA-E awardees were about 60 percent more likely to publish at least one paper as a result of their ARPA-E projects than recipients of awards from OS, for which publication is a primary objective. Even after controlling for many variables that might explain this raw differential, the study found that awards from the two agencies produced publications at roughly the same rate and in similar quality journals, and they received approximately the same number of citations.[42] That is a surprising and, for ARPA-E, encouraging finding, considering that OS funds laboratory researchers with strong incentives to produce peer-reviewed publications.

Patents differ from publications in that they describe inventions, which must not only be novel, but also useful. In addition, a patented invention must be "reduced to practice;" it has to actually work and cannot simply be an idea. Nonetheless, most patented inventions are remote from widespread application. Large sums of money and years of further work are usually required to turn an invention into something that makes money for a company, much less provides substantial value to society. In this sense, a patent is similar to a publication in that each signals potential, rather than the realization of an outcome. Patent citations provide further insight into patent quality.

The National Academies' committee compared the likelihood of ARPA-E awardees patenting with that of awardees of one of DOE's applied energy offices, the Office of Energy Efficiency and Renewable Energy (EERE). In the time period studied by the committee, 13 percent of ARPA-E's awards had resulted in a patent, compared with 5 percent of EERE's. ARPA-E produced one patent for each $8.2 million award, whereas the comparable figure for EERE was $28.4 million. ARPA-E patents were also more likely to be cited by later patents.[43]

Building on the National Academies' study, recent work by Anna P. Goldstein and Venkatesh Nanayanamurti supplies an even more encouraging finding. After thoroughly controlling for variables that might confound the relationship, they find that ARPA-E awardees are at least five times more likely to produce both a patent and a publication than awardees of OS or EERE.[44] In other words, many ARPA-E projects are producing *both* basic research that is available in the public domain to any peer *and* intellectual property that may serve as the basis for the creation of marketable products and services. ARPA-E is thus able to expand the boundaries of scientific fields relevant to energy innovation while simultaneously serving as a conduit for impactful applied research. Box 1 describes one of ARPA-E's most successful awardees in these regards, Hong-cai Zhou, professor and holder of a Robert A. Welch chair in chemistry at Texas A&M University.[45]

Proof of Concept and Validation: Follow-On Funding

Publications and patents signal the potential for innovation that will ultimately contribute to ARPA-E's mission. They certify the technical validity and legal novelty and utility of new concepts. Proof of concept and validation are activities that are closer to practical use and to the market than the concept formulation that lead to publications and patents. These activities involve the development of products and services with identifiable use cases, customers, and cost profiles. For example, Primus Power used its ARPA-E award to build zinc-based flow batteries for use by large-scale utility, commercial, and industrial customers. 24M's award helped it develop hybrid batteries for use in electric vehicles (see box 2 below.)[46] Compared to publications and patents, the creation of new things gives private investors a much clearer understanding of the potential for the companies that made these things to make money as well. It therefore increases the odds of investment.

BOX 1: HONG-CAI ZHOU, TEXAS A&M UNIVERSITY, HIGHLY-CITED CHEMICAL RESEARCH WITH DIVERSE APPLICATIONS TO CLEAN ENERGY

Professor Hong-Cai Zhou, Robert A. Welch chair in the Chemistry Department at Texas A&M University received ARPA-E awards in 2010 and 2012. These awards exemplify the agency's ability to support projects that are both of great use to the basic research community, as indicated by their impressive publication and citation results, and immediately applicable to practical problems, as demonstrated by the spinoff of a company that has raised almost $2 million in start-up funding.

Zhou's research focuses on metal-organic frameworks (MOFs). These unusual compounds have extraordinarily large internal surfaces; "once unraveled, one sugar-cube-sized piece could cover an entire football field." They are also easily modified or "tuned" so that they can be used as molecular sieves that precisely separate targeted compounds. MOFs are notoriously unstable, which has limited their utility in the past, but Zhou's group has found ways to strengthen their internal bonds and make them "ultra-stable."

MOFs have a variety of potential uses in the clean energy domain. Zhou's first ARPA-E project focused on developing MOFs that could bind to carbon dioxide using much less energy than established methods. These compounds might ultimately be used to capture carbon dioxide at an affordable cost from the flue gases produced by fossil fuel-fired power plants. His second ARPA-E award focused on creating MOFs for low-pressure natural gas storage. The work of Zhou's team increased MOFs performance of this task, while radically reducing the cost, which could aid in the development of alternative-fuel vehicles.

Since the beginning of 2010, Zhou has authored or co-authored 136 papers, which have received more than 8000 citations. Twenty-three of these papers have received more than 100 citations, and 25 of them rank in the top 1 percent of all papers published in a particular year and field. Zhou specifically references his first ARPA-E award in 28 papers that have garnered nearly 3000 citations and his second one in 25 papers that have already been cited nearly 1000 times since only 2014. He is also a prolific author of review papers, one of which is the citation champion among ARPA-E performers, receiving 2760 citations to date.

Zhou's scientific work led to the establishment of framergy, a start-up firm that licenses MOF technology from Texas A&M. Framergy's goal is to convert MOFs into a high volume, high quality, low cost product for clean energy and other applications. The firm has received two rounds of financing, totaling $1.85 million and has a strategic relationship with a global Tier 1 auto supply firm.

As noted above, ARPA-E project teams formed 56 new companies and raised more than $1.8 billion in private-sector follow-on funding in the first eight years of the agency's existence.[47] Additionally, ten companies have successfully attained exits, seven through acquisition and three through initial public offerings. In total, 14 ARPA-E companies have already released commercial products, which is impressive given the agency's short history and the long duration of most energy innovation processes.[48] We expect this indicator to rise significantly as the technologies supported by ARPA-E continue to mature.

These raw data provide valuable evidence of the important contributions that ARPA-E has made not only to the creation of knowledge, but also to its translation into use. In this section, we add to this evidence with an analysis of clean energy investment by private equity firms, including venture capital firms. We show that ARPA-E funding fills a void left by the capital markets, making it possible for the most promising startup companies to secure private (and non-ARPA-E government) funding that will carry them closer to and eventually into the market.

Boom and Bust in Early Stage Energy Investing

The first step in our analysis describes the dynamics of private investment in energy startups. Venture capital investing is prone to cycles and fads, and investments in early-stage energy firms provide a vivid example of this behavior in the first part of the 21st century.[49] The boom and bust were particularly severe for energy hardware companies. This shift is consistent with a broader shift from hardware to software among venture capitalists across all sectors. These investors increasingly prefer firms that can experiment quickly and inexpensively to those with long R&D timelines. The bust has created severe financing constraints for energy hardware startups.[50]

To assess the landscape of deals in what has become known as the “cleantech” sector, we compiled a data set of 1,987 investments across 919 firms in the United States since 2000 using the Prequin Private Equity Deals Database. We used a broad definition of this sector. Each deal corresponds to a unique investment round for a given company. We distinguished each deal in the sample as a deal corresponding to an early-stage investment (seed rounds, Series A, and Series B) and later stage investments (growth equity). We then distinguished each company by the type of product it produced, among hardware, software or project finance (or other) firms. We also created narrower technology categories for each company, such as advanced materials, smart grid, biofuels, and so on. More details on the construction of the database and full descriptive statistics can be found in the appendix. A full descriptive statistics can be found in appendix table 1.

The average deal size in the sample is $16.7 million, but this distribution is highly skewed; 72 percent of the deals are smaller than the mean deal. Twenty-one percent of the deals are obtained by software firms, 60 percent by hardware firms, and the remaining 19 percent by project development and/or service firms.

Figures 3 and 4 show the boom and bust in the cleantech sector over the past 15 years. The number of deals peaked at 153 in 2008 before falling to 80 in 2016, and it is on pace to be only 73 this year. The dollar amounts rise and fall even more dramatically. With only $290 million invested in 2005, investors piled into the clean energy sector to the tune of $3.2 billion in 2008. The fall was nearly as precipitous, to about $1.1 billion in 2013, stabilizing below $1 billion in the years since. Prominent venture capitalists like John Doerr were among those who took significant losses.[51]

Figure 3: Number of private equity cleantech deals, 2005-2017

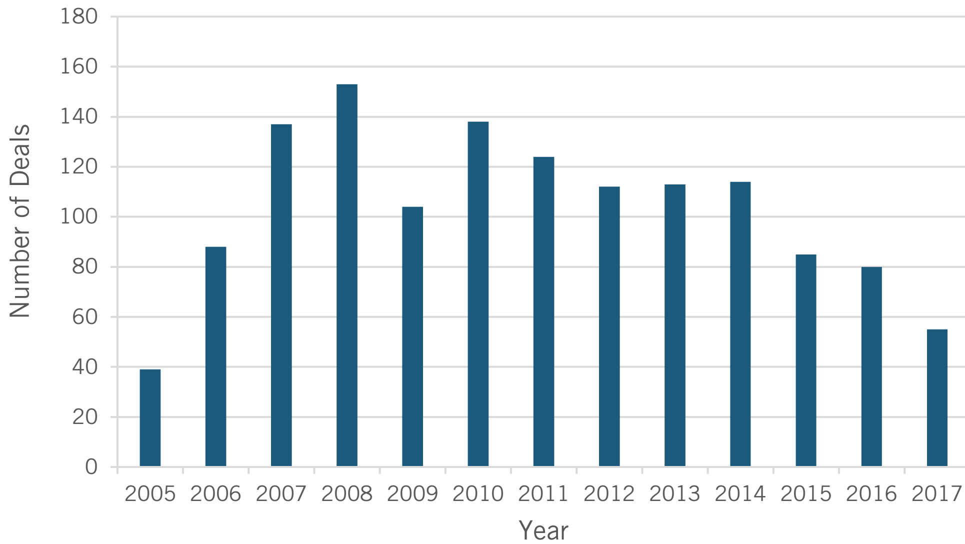
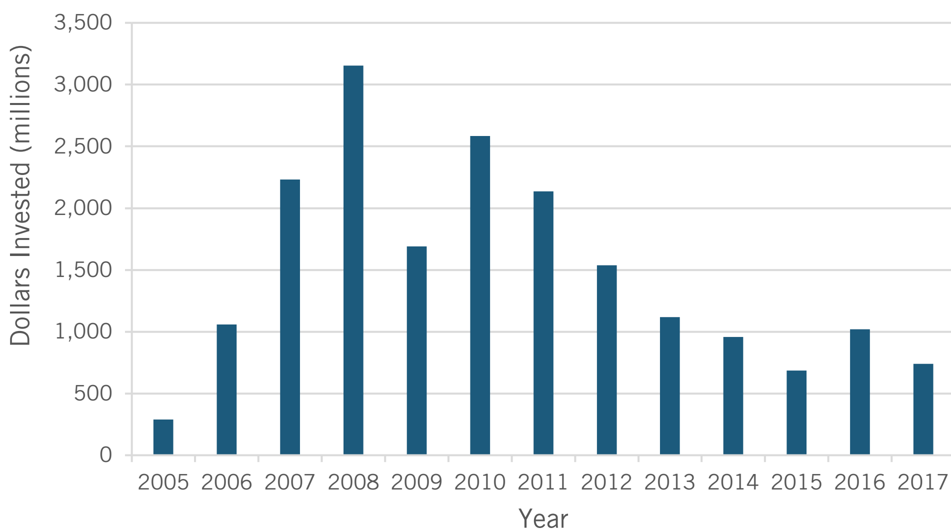


Figure 4: Dollars invested in private equity cleantech deals, 2005-2017



This herd behavior is unsurprising given the poor performance of clean energy investments in this period. Ben Gaddy, Varun Sivaram and Frank O'Sullivan found that investments in this sector between 2006 and 2011 lost more than 50 percent of their value.[52] Moreover, whereas successful clean-tech investments returned 8.6 times the initial investment, successful investments in software companies did even better, returning 11.6 times the initial investment. Gaddy, Sivaram, and O'Sullivan conclude that the venture capital funding model does not fit well with many energy innovation processes, which have a long timeline for experimentation, development and deployment. The impatience and poor payoff experienced by cleantech venture capitalists were also evidenced in some federallyfunded deployment programs in this period, which sought to force maturation of technologies that may not yet have been ready.

Figures 5 and 6 show that the decline in venture capital funding for energy startups was not universal across the sector. Instead, the decline focused disproportionately on hardware-technology-development firms. In 2006, hardware firms received five times the number of investments as software firms in the sector and an order of magnitude more funding ($756 million to $73.4 million). This ratio began to shift around 2010 and gradually transitioned toward software firms. In 2016, software firms overtook hardware firms in the amount of funding received, and recent years suggest that this is the new normal in the sector.

Figure 5: Number of hardware and software private equity cleantech deals, 2005-2017

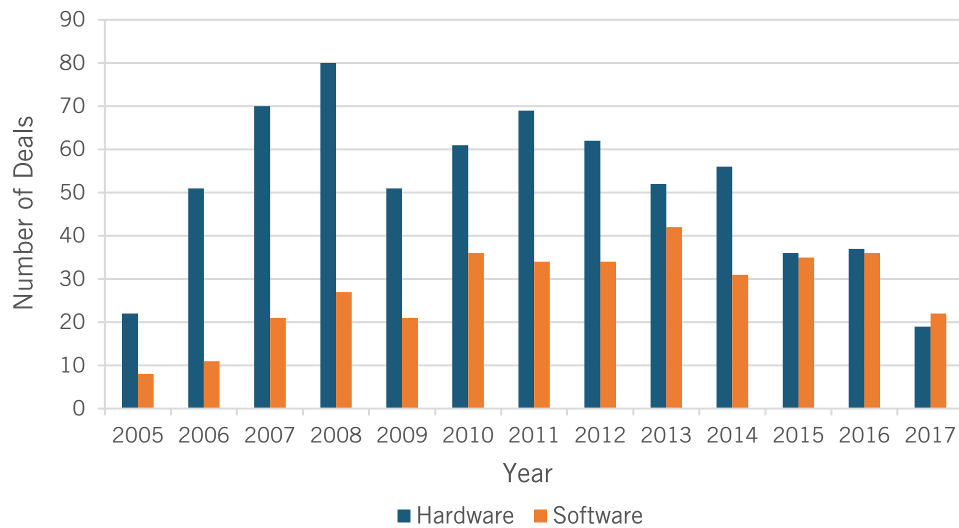
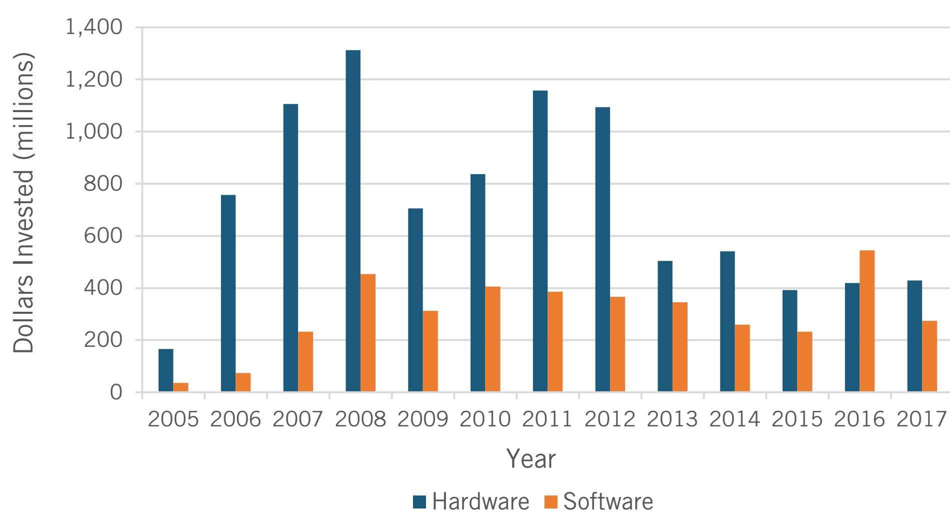


Figure 6: Dollars invested in hardware and software private equity cleantech deals, 2005-2017



Figures 7–10 demonstrate that the same pattern holds even more starkly when we confine the data to early-stage investments. Figure 7 shows that the number of early stage deals in the clean energy sector peaked at 109 in 2008. After stabilizing at around 70, the number fell to 54 in 2016, with roughly the same number of deals projected for 2017. Measured in dollars in figure 8, the drop-off is well over 50 percent from the 2008 peak of $1.5 billion, landing below $500 million since 2011.

Figure 7: Number of early-stage private equity cleantech deals, 2005-2017

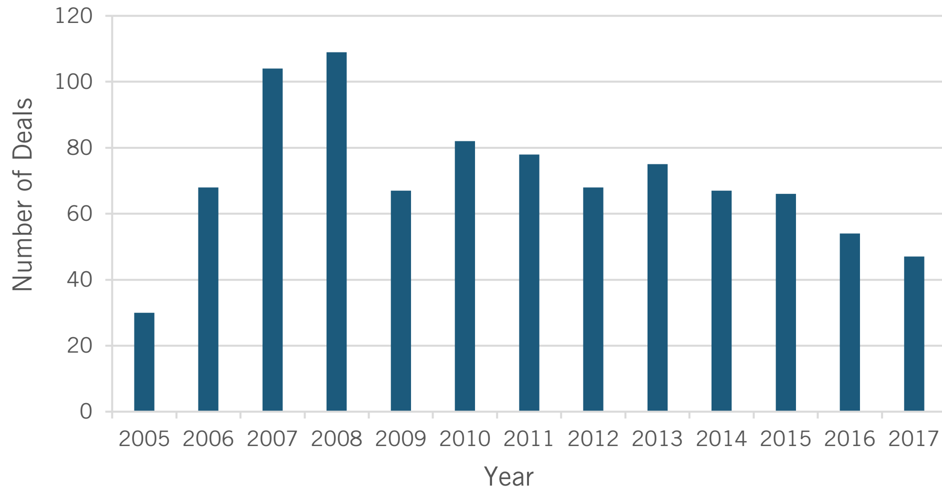
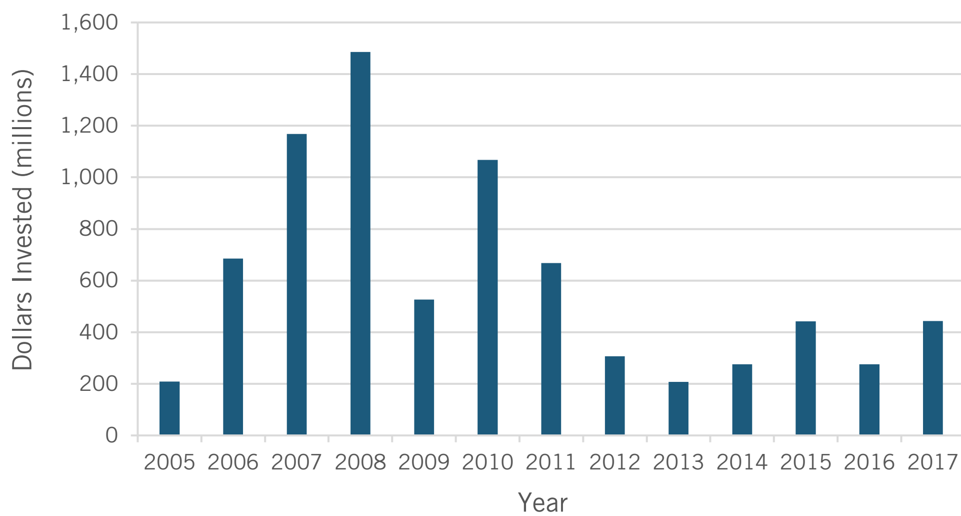


Figure 8: Dollars invested in early-stage private equity cleantech deals, 2005-2017



Figures 9 and 10 display the division between hardware and software investments in deals and dollars respectively. Clean energy software companies have actually been able to raise early stage funding at a rising rate, from $15.4 million dollars over five firms in 2005, to $128 million dollars over 24 firms in 2016. Funding for hardware firms, by contrast, precipitously declined from a peak of $630 million in 2007 to a low of $69 million in

2013, an order of magnitude reduction in only six years. Funding levels for hardware firms have stabilized around $140 million thereafter, well below the trend for the previous decade.

Figure 9: Number of early-stage hardware and software private equity cleantech deals, 2005-2017

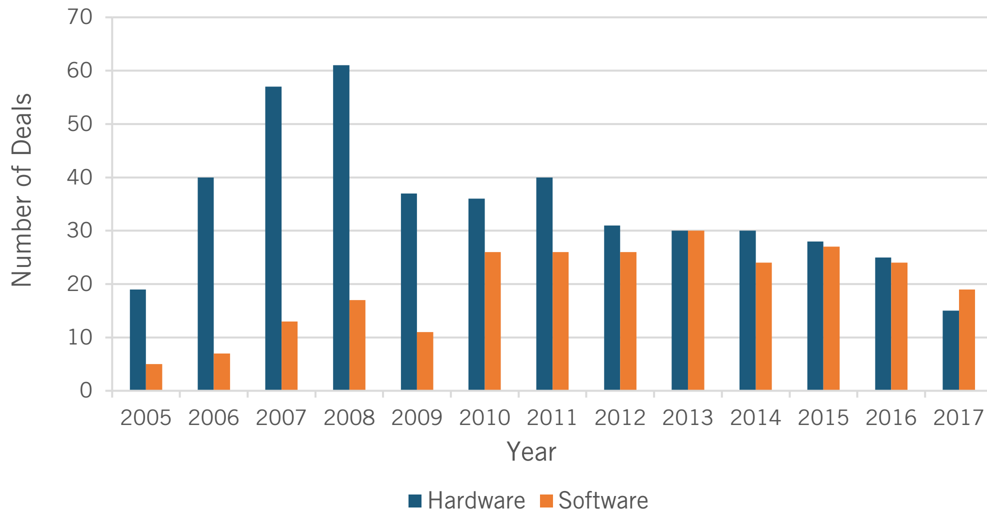
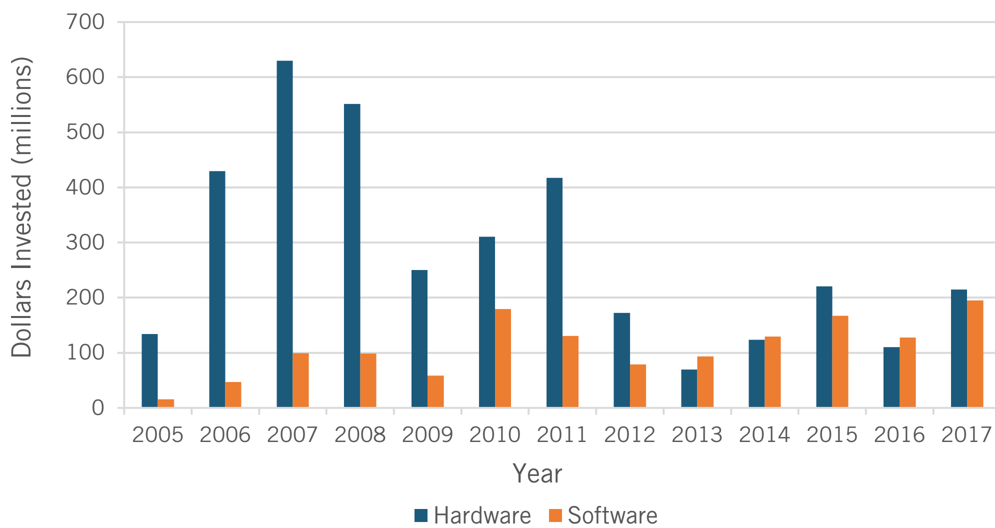


Figure 10: Dollars invested in hardware and software private equity cleantech deals, 2005-2017



The descriptive evidence provided here is illustrative of the market failure in the promotion of early-stage energy innovation, particularly for hardware technologies, as predicted by economic theory and explored by other researchers. It is important to note that this phenomenon is relatively recent, occurring after the launch of ARPA-E in 2009. The boom and bust experience of venture capital in the 2000s can be seen as a failed institutional innovation. Venture capitalists tried to apply their established model in a domain in which it fit poorly, as Gaddy, Sivaram, and O'Sullivan argue. In the absence of ARPA-E, this situation would continue to devolve. The important question becomes to what extent ARPA-E can sufficiently de-risk technology to create more deal-ready firms. We turn to this analysis in the next section.

Follow-on Funding for ARPA-E-funded Startups

To assess the role of ARPA-E within this financially constrained environment, we added two more variables from publicly available sources to the firm-specific information about energy innovation investment deals that we have described above. The first indicates whether a firm received an award from ARPA-E. The second indicates whether the firm received support from a government agency other than ARPA-E, which provides a second pathway to commercialization in addition to private investment (see box 3).[53] We then use regression analysis to evaluate the relationship between the receipt of ARPA-E funds and the securing of follow-on funding from private or public sources. We also explore whether ARPA-E-backed firms raise more money than comparable firms and therefore appear in the top half or top ten percent of the fundraising distribution.

Firm-level descriptive statistics are provided in appendix table 2. Hardware firms comprise 56 percent of the sample, while software firms make up 21 percent. The remainder includes project development, service or other types of firms. The firms are distributed evenly across different technology categories, with the largest subset in the data (16 percent) being solar firms. Eleven percent of firms have received ARPA-E funding.

Table 1 presents the results of the regression analysis. The key independent variable is whether or not a firm received an ARPA-E award. We control for the age and subsector of each company and whether it is identified as a hardware firm in the sample. We find that ARPA-E-funded firms, on average, raise more money than other clean energy startups.

Table 1: Regression Analysis of ARPA-E Funding Impact on Follow-On Funding

	(1) Follow-on Funding	(2) Top 50th Percentile	(3) Top 10th Percentile	(4) Gov. Funding
ARPA-E	0.521* (0.293)	0.731* (0.404)	1.698*** (0.509)	1.031** (0.411)
Hardware	-0.084 (0.249)	-0.112 (0.360)	0.772 (0.892)	0.019 (0.518)
Year Founded	-0.211*** (0.033)	-0.213*** (0.056)	-0.474*** (0.104)	-0.086 (0.069)
Tech Sector Fixed Effects	YES	YES	YES	YES
Model	OLS	Logit	Logit	Logit
Observations	320	318	286	314
R2	0.203			

Standard errors in parentheses
Prequin Data Full Sample
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

BOX 2: ENERGY STORAGE—BREAKING THROUGH A CLEAN ENERGY INNOVATION BOTTLENECK

ARPA-E has put about 10-15 percent of its cumulative funding into the science and technology of energy storage. Including its very first FOA in 2009, it has carried out three focused programs in this field and funded numerous additional projects through open solicitations. ARPA-E's support has helped bring affordable, reliable energy storage much closer to reality than it was just eight years ago.

The inability to store electricity at a reasonable cost is the largest constraint on electric power and transportation systems. Without storage, power must be delivered immediately after it is generated, requiring grid managers to match the load every minute of the day. Without storage, the variability of renewables raises the risk of curtailment and brownouts. Without storage, electric propulsion will never challenge the internal combustion engine, ruling out achieving deep cuts in transportation-generated greenhouse gas emissions.

The National Academies' committee found that ARPA-E's 63 awards in the energy storage "white space" had yielded 115 papers and 22 patents. More important, the rates of company founding and follow-on funding in this field outpaced the rest of ARPA-E's awards. Six of the 63 projects resulted in new companies being formed, and 20 of them accessed follow-on funding after their ARPA-E awards expired. As of the end of 2016, four ARPA-E companies had a mass-manufactured product on the market. The committee noted that two ARPA-E energy storage programs, Batteries for Electric Energy Storage in Transportation and Grid-scale Rampable Intermittent Dispatachable Storage, were "highly productive with respect to accelerating commercialization."

Two of the most exciting examples of the payoff from ARPA-E's funding of energy storage are Primus Power and 24M. Thanks in part to ARPA-E's early $2 million award, Primus Power is now commercializing a zinc-based flow battery with the potential to provide power to the grid on a large scale that is competive with natural gas-powered peaker plants, a market expected to exceed $68 billion by 2024. Primus deployed its first system to Marine Corps Air Station Miramar in 2015 to create a secure, reslient renewable-powered microgrid. It has raised over $100 million in venture funding from domestic and international investors.

24M is targeting the vehicle storage market. Today's electric vehicles use lithium-ion batteries that have inherent limitations due to their cost, weight, lifespan and capacity. 24M seeks to combine lithium ion technology's fast response and high power with the longer duration capabilities of flow battery technology. 24M has raised $50 million to date with investment from Charles River Ventures, Northbridge Partners, and three strategic industrial partners.

BOX 3: ARPA-E, DARPA AND THE DEPARTMENT OF DEFENSE

Although ARPA-E has successfully adopted many of the critical active management practices established and utilized by DARPA over the last half-century, there remain some important differences that should be considered as ARPA-E evolves in the year to come. Most notably, DARPA's portfolio of projects has a built-in end-customer, the United States military, whereas this is not the case for ARPA-E performers.

However, as of March 2016, 22 start-up firms funded by ARPA-E had received follow-on support from a unit within the Department of Defense. The United States military is the single largest consumer of energy in the world. It increasingly recognizes that energy innovation is vital to performing its mission, by lowering costs, improving reliability and resilience, and protecting our troops.

ARPA-E has also explored more a more formal partnership with the United States Navy. In 2010, ARPA-E released a Funding Opportunity Announcement for the program "Building Energy Efficiency Through Innovative Thermodevices (BEETIT)." Performers were charged with developing breakthrough advances in building cooling equipment and air conditioning, which currently account for 72 percent of the United States's electricity use.

Given the program's potential impact for military installations, ARPA-E partnered with the Navy for a second round of funding for a select group of BEETIT performers, with the focus on improving fuel efficiency by 20-50 percent for soldiers in extreme conditions. An additional $8.5 million was allocated to five companies. This approach accomplishes two important objectives. First, it allows for the continued support of ARPA-E recipients that have performed well, i.e. those recipients are not funded into a vacuum of private sector funding to die on the vine. Second, it creates a direct pathway to engagement with the Department of Defense, an important first customer.

Efforts like this to bridge the gap between research and commercialization for defense applications are important for further maturing worthy ARPA-E projects, and could be reproduced in the future.

In models two and three, we consider whether ARPA-E funded firms have a greater likelihood of being in the top part of the fundraising distribution. In model two, we find that the odds of a firm being in the top half of the follow-on funding distribution given the receipt of ARPA-E funding doubles (log odds ratio of 0.731). More importantly though, model three shows that ARPA-E funding is associated with a five-fold increase in the odds of being in the top 10 percent of the fundraising distribution (log odds ratio of 1.698). In entrepreneurship, where the outcomes that matter are those in the tail of the distribution, this finding is of critical importance. Model four, similarly, shows that ARPA-E funding is associated with a three-fold increase in the odds that a firm will receive funding from another government agency as it scales up (log odds ratio of 1.031).

We can have very high confidence that these regressions are providing meaningful information, because of their very low p values. For models one and two, the p values are less than 0.1, which means that the odds of the relationship occurring by chance are under one in ten. Our confidence in the other models is even higher, with p values indicating that the odds of the relationship occurring by chance are under one in a hundred in model three and under one in 20 in model four. For additional robustness, we confirmed these relationships using OLS in models two through four, as shown in appendix table 3.

It is possible that ARPA-E selects better candidates for follow-on funding to begin with. Our control variables help to address this objection. In addition, this interpretation runs up against our prior observation that program directors impose their idiosyncratic views during project selection, rather than accept the views of peer reviewers. As we have seen in this section, venture capitalists, like peer reviewers, suffer from conformism, and it is unlikely that their judgments would have corresponded to those of the program directors. The more likely interpretation of these findings is that ARPA-E-funded firms have an advantage over other firms because their ARPA-E funding has enabled them to reduce the level of technological uncertainty and helped to signal the quality of the technology to potential investors. With reduced uncertainty, investors can more suitably fit these companies into a venture capital portfolio and invest a larger amount of money with confidence.

CONCLUSIONS AND RECOMMENDATIONS

If the nation is going to meet the challenges of the 21st century and improve energy affordability, security, resilience, safety, and sustainability, our energy innovation system needs to change.

The U.S. energy innovation system is struggling. Energy is not yet as cheap or as clean as it should be or could be. Transformational innovations that will bring the United States into the post-fossil-fuel era are too few and too immature. The electric grid today looks much like it did a century ago. The reasons behind this dismal performance are clear. U.S. energy markets do not effectively incentivize energy innovation, particularly transformational energy innovation, so firms underinvest in activities that would lead to it. The Department of Energy's science and applied energy programs fill some of the gaps left by the market, but not all of them. If the nation is going to meet the challenges of the 21st century and improve energy affordability, security, resilience, safety, and sustainability, our energy innovation system needs to change.

ARPA-E represents one kind of needed change. With just a few years under its belt in a game that is played over the long term, this small agency has already begun to deliver excellent results. Its novel structure and operating procedures allow it to recruit and empower strong and creative leaders who are willing to tackle difficult and important problems that no other entity in the energy innovation system will. It has created a culture of innovation in an environment that is highly risk-averse. ARPA-E awardees perform well on conventional metrics of scientific and technological output, such as publications and patents. They also perform well on metrics that have not always been adequately valued in energy policy, such as company formation, technological maturation, and commercialization.

ARPA-E will not solve all of the problems facing energy innovators. Consumer biases, regulatory rigidities, and the sheer difficulty of the technical challenges are among the barriers that stand between the prototypes that ARPA-E-funded firms develop and their large-scale adoption. But the broader the portfolio of technological options, the higher the odds that some innovations will surmount these barriers. Over time, energy innovation will feed on itself and create pressure to reduce the barriers to making energy cleaner and cheaper.

ARPA-E's potential has not yet been fulfilled. Our analysis leads us to make the following recommendations:

Maintain ARPA-E's operational autonomy and distinctive operating procedures. ARPA-E was designed to be nimble and flexible. These qualities are essential to its effectiveness and its distinctive innovation-oriented culture. Above all, ARPA-E must be able to continue to hire program managers on a temporary basis from outside the federal system in a reasonably speedy manner. These managers must continue to have the authority to define new programs and select projects, which is what draws them into federal service. Although consultation and collaboration between ARPA-E and the rest of DOE should be encouraged, efforts by DOE headquarters and senior management to exert greater control over ARPA-E should be resisted.

Expand ARPA-E's budget. Energy innovation covers a vast domain of applications. ARPA-E has touched many, ranging from power, transportation, and buildings to agriculture, industry, and smart cities. Yet, there are many more "white spaces" that have not been adequately explored, both within these areas and beyond them. The impressive responses to ARPA-E solicitations suggest that there is no shortage of potential innovators. ARPA-E's management approach is modular, so adding new programs or expanding existing ones seems unlikely to create significant additional overhead. We therefore concur with the recent report of the American Energy Innovation Council, a group of ten private-sector leaders, including Microsoft founder Bill Gates, that ARPA-E's budget should grow toward the $1 billion target set by the 2005 National Academies *Gathering Storm* report.[54]

Reauthorize ARPA-E. ARPA-E was established during the George W. Bush administration and has received bipartisan support in Congress since then. That kind of support continues in the current effort to reauthorize the agency. A large and growing group of Republican and Democratic members of the House of Representatives is co-sponsoring this legislation (HR 3681). It is backed by a diverse array of non-governmental organizations ranging from the U.S. Chamber of Commerce and the American Council for Capital Formation to the American Council on Renewable Energy and Environmental Entrepreneurs. Reauthorization would send a strong signal that ARPA-E's autonomy should be maintained and lay the groundwork for expanding its budget.

Establish an ARPA-E trust fund to stabilize its budget and fund it with royalties from oil and gas production on federal lands. Stability and certainty are nearly as important as scale in public support for innovation activities. In an era of federal constraint, sustaining ARPA-E funding at the appropriate level will undoubtedly be difficult. ITIF therefore recommends that a portion of the revenues from oil and gas exploration on federal lands and offshore tracts be dedicated to an ARPA-E trust fund.[55]

Infuse ARPA-E practices into the rest of DOE. The National Academies' *Assessment of ARPA-E* hailed it as "a positive agent of change in DOE and the federal government" as a whole and notes that some DOE offices have been receptive to adopting its practices.[56] Personnel recruitment, contracting, project management, and R&D topic development are among the areas of practice that might be considered in this regard. ARPA-E cannot and should not be replicated throughout DOE. Large-scale technology demonstrations and blue-sky scientific research are among the many activities that the department undertakes that would not fit the ARPA-E model. But the adoption of bits and pieces, and occasionally whole chunks, of the model would improve the performance of DOE's famously byzantine bureaucracy.

APPENDIX A: EARLY STAGE CLEAN ENERGY INVESTMENT DATA

The data used in this analysis is drawn from the Prequin Private Equity Deals Database. The database was accessed on October 24, 2017 through MIT's institutional account. All deals (Add-on, Angel, Grant, Growth Capital/Expansion, PIPE, Pre-IPO, Seed, Series A-L) from the "Clean Technology" and "Energy and Utilities" industry groups were included. These groups contain the Clean Technology, Environmental Services, Renewable Energy, Energy, Oil & Gas, Power, and Utilities industries. These industries, in turn, include the following subindustries: advanced components, advanced materials, air quality, automotive components, batteries, biofuels, biopolymers, bioremediation, carbon credit, clean coal, efficiency infrastructure, electric/hybrid vehicles, emissions control, energy storage, fuel cells, green IT, grid management systems, intelligent network devices, intelligent sensors, lithium ion batteries, materials, molecular chemicals, nanopower, nuclear, power generation, recycling, solar thermal, solid state lighting, supercapacitors, sustainable agriculture, transportation, waste management, waste to energy, water purification and recycling, biomass, geothermal, hydro power, solar power, wind power, air conditioning equipment and products, electric energy distribution, heating equipment and products, natural gas production and distribution, oil and gas exploration and production, oil and gas field services, petroleum refining, petroleum wholesale distribution, electric power generation, motors and generators, waste management, and water and sewer utilities.

Appendix tables 1 and 2 provide descriptive statistics for the database.

Appendix Table 1: Descriptive Statistics for Clean Energy Investment Level Dataset

Variable	Mean
Deal Size (USD mn)	$16.67
Year Founded	2006.8
Seed Investments	13%
Series A Investments	25%
Series B Investments	21%
Growth Equity Investments	41%
Hardware Company	60%
Software Company	21%
Other (Company Type)	19%
Advanced Materials	4%
Energy Efficiency	10%
Energy Storage	11%
Fuel Cells	2%
Smart Grid	3%
Solar	17%
Biofuels	9%
Conventional	5%
Transportation	7%
Biomass	1%
Wind	3%
Nuclear	1%
Other (Tech Sector)	27%
Observations	1987

Appendix Table 2: Descriptive Statistics for Clean Energy Firm-Level Dataset

Variable	Mean
Year Founded	2007.2
Total Capital Raised	$31,000,000
Hardware Firm	56%
Software Firm	21%
Project Dev / Service / Other	23%
Advanced Materials	6%
Energy Efficiency	9%
Energy Storage	9%
Fuel Cell	2%
Smart Grid	3%
Solar	16%
Biofuels	7%
Conventional	6%
Transportation	6%
Biomass	1%
Wind	3%
Nuclear	1%
Other Tech Sector	30%
ARPA-E	11%
Observations	919
Variable	Mean
Year Founded	2007.2
Total Capital Raised	$31,000,000

Appendix Table 3: Regression Results using OLS

	(1) Follow-on Funding	(2) Top 50th Percentile	(3) Top 10th Percentile	(4) Gov. Funding
ARPA-E	0.521* (0.293)	0.151* (0.080)	0.171** (0.069)	0.180** (0.080)
Hardware	-0.084 (0.249)	-0.022 (0.083)	0.039 (0.037)	0.002 (0.056)
Year Founded	-0.211*** (0.033)	-0.046*** (0.011)	-0.026*** (0.005)	-0.010 (0.008)
Tech Sector Fixed Effects	YES	YES	YES	YES
Model	OLS	OLS	OLS	OLS
Observations	320	320	320	320
R2	0.203	0.143	0.165	0.141

Standard errors in parentheses
OLS regression
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

ENDNOTES

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