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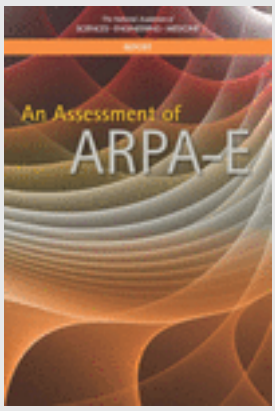

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AN ASSESSMENT OF ARPA-E

Committee on Evaluation of the Advanced Research Projects Agency-Energy (ARPA-E)

Board on Science, Technology, and Economic Policy
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Board on Energy and Environmental Systems
Division on Engineering and Physical Sciences

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Preface

In 2005, the National Research Council (NRC) report *Rising Above the Gathering Storm* recommended a new way for the federal government to spur technological breakthroughs in the energy sector. It recommended the creation of a new agency, the Advanced Research Projects Agency-Energy, or ARPA-E, as an adaptation of the Defense Advanced Research Projects Agency (DARPA) model—widely considered a successful experiment that has funded out-of-the-box, transformative research and engineering that made possible the Internet, GPS, and stealth aircraft. This new agency was envisioned as a means of tackling the nation's energy challenges in way that could translate basic research into technological breakthroughs while also addressing economic, environmental, and security issues. It was unclear ex ante whether such an adaptation would work, whether an ARPA-E engineered from the ground up to be lean, agile, and independent would be effective at catalyzing the transformation of energy technologies as DARPA had been with other technologies. Accordingly, *Rising Above the Gathering Storm* also recommended that ARPA-E be independently reviewed after some years of operation. When Congress authorized ARPA-E in the 2007 America COMPETES Act, it followed the recommendations both to create the agency and to request an early assessment following 6 years of operation to examine the agency's progress toward achieving its statutory mission and goals. This report documents the results of that assessment.

Now 7 years into its operations, ARPA-E is demonstrably built on the DARPA model while differing in certain respects. People form the core of the agency. Program directors are hired for limited terms; highly empowered to act outside of the box when designing new programs; expected to search for, identify, and support high-risk but potentially high-impact projects; and substantially involved in managing the research and technical aspects of funded projects. ARPA-E is characterized by institutional independence and a flat organizational structure, and it can quickly initiate and terminate projects based on performance. The agency has tailored the DARPA model to include in-house contracting so that funding decisions can be made much more quickly relative to most government funding agencies. It also has developed a continuously evolving system intended to aid project teams in preparing for the eventual development of their technologies into commercial products.

The assessment documented in this report is based on currently available data and analytical methods, and should be useful to ARPA-E as it continues to evolve and improve its operations and programs. In addition, the report provides valuable information for Congress as input to its decisions regarding ARPA-E's future, and for scholars and stakeholders within the energy technology innovation system who study or interact with ARPA-E and other participants in that system. Independent reviews can provide reliable, external indicators of the performance of government programs or agencies. A number of the analyses conducted for this assessment take

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advantage of analytical methods developed only recently. As increases in computing power and the unlimited ingenuity of the human mind continue to expand the frontiers of analytical methodology and thus the value of assessments, this report can serve as a vision of what is possible, as well as a glimpse of how much more would be possible with additional data, time, and other resources.

Since 1991, the NRC, under the auspices of the Board on Science, Technology, and Economic Policy (STEP), has undertaken a program of activities designed to improve policy makers' understanding of the interconnections among science, technology, and economic policy and their importance for the American economy and its international competitive position. STEP's activities have corresponded with increased policy recognition of the importance of knowledge and technology to economic growth. New economic growth theory emphasizes the role of technology creation, which is believed to be characterized by significant growth externalities. Likewise, under the auspices of the Board on Energy and Environmental Systems (BEES), the NRC has undertaken a program of studies and other activities to provide independent advice to the executive and legislative branches of government and the private sector on issues in energy and environmental technology and related public policy. BEES directs expert attention to issues surrounding energy supply and demand technologies and systems, including resource extraction through mining and drilling; energy conversion, distribution and delivery, and efficiency of use; environmental consequences of energy-related activities; environmental systems and controls in areas associated with the production, energy conversion, transmission, and use of fuels; and related issues in national security and defense.

A central focus of NRC analysis has been the importance of energy innovation to the growth of the U.S. economy and to the reduction of negative environmental, public health, and other consequences of energy-related activities. Many performance gains in energy technologies remain to be achieved, such as the capture of carbon from the use of fossil fuels, advanced nuclear power from fission and fusion, renewable fuels for electricity generation and for vehicles, and increasingly efficient use of energy. Yet undertaking the efforts required to produce the innovations needed to transform the performance of the energy sector so as to mitigate the risks from energy production, conversion, and consumption may be the greatest challenge humanity has ever faced. It is a worldwide challenge demanding tremendous effort and leadership. Throughout history, the United States has consistently demonstrated that its greatest resource is its people and their talent for innovation and leadership. There has never been a greater need or opportunity for American leadership than that posed by the challenge of achieving dramatic innovations in energy technology, a challenge that is the subject of this report.

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On behalf of the National Academies of Sciences, Engineering, and Medicine, the committee expresses its appreciation for and recognition of the insights, information, experiences, and perspectives provided by the many participants in workshops and roundtables held during the course of this study. We would particularly like to recognize Anna Goldstein, Tom Howell, and Michael Kearney for their invaluable research and technical assistance in the preparation of this report. We also thank Frederic Lestina, Erik Saari, Alisa Decatur, and Rona Briere for their assistance in preparing this report for publication.

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Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the process.

We wish to thank the following individuals for their review of this report: Gary Anderson, National Institute of Standards and Technology; Ewa Bardasz, Zual Associates in Lubrication LLC; Harvey Blanch, University of California, Riverside; William Brinkman, Princeton University (retired); Douglas Cameron, First Green Partners; Maryann Feldman, University of North Carolina; Shane Greenstein, Harvard University; Douglas Kirkpatrick, InnerProduct Partners; Gerald D. Mahan, Pennsylvania State University; Ramana Nanda, Harvard University; and David Popp, Syracuse University.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Robert Frosch, Harvard University (retired), and Michael Ladisch, Purdue University. Appointed by the National Academies, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Pradeep Khosla
Committee Chair

Paul Beaton
Study Director

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Summary

Under a mandate from the U.S. Congress, the Advanced Research Projects Agency-Energy (ARPA-E) asked the National Academy of Sciences to conduct an assessment of the progress the agency has made toward achieving its congressionally mandated mission and goals. This report includes both an operational assessment of the agency's funding programs and a technical assessment of its awards, to the extent possible. The ad hoc committee convened to conduct this assessment relied on quantitative and qualitative analyses of data on ARPA-E's creation of technology-focused funding programs, its decision-making processes for granting awards, its management of projects and awardees, the patenting and publishing activities of awardees, and further investments made in awardee projects following ARPA-E funding.

There are clear indicators that ARPA-E is making progress toward achieving its statutory mission and goals, and it cannot reasonably be expected to have completely fulfilled those goals given so few years of operation and the size of its budget. Importantly, especially at this early stage, the committee found no signs that ARPA-E is failing, or on a path to failing, to deliver on its mission and goals. From its complete set of 18 findings, the committee developed 14 recommendations, which are listed in full at the end of this summary. This summary presents an overview of the study and highlights the 5 findings and 5 recommendations the committee believes are most important. The complete list of the committee's findings and recommendations is presented in Boxes S-1 and S-2, respectively, at the end of this summary.

SCOPE OF THE ASSESSMENT

The first part of the committee's task was to assess the progress ARPA-E has made toward achieving its statutory mission and goals during the first 6 years of its operation and whether it is on a trajectory to achieve them. Congress established the agency with a mission "to overcome the long-term and high-risk technological barriers in the development of energy technologies," and specific goals to

> "(A) enhance the economic and energy security of the United States through the development of energy technologies that result in—
> (i) reductions of imports of energy from foreign sources;
> (ii) reductions of energy-related emissions, including greenhouse gases; and
> (iii) improvement in the energy efficiency of all economic sectors; and

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(B) ensure that the United States maintains a technological lead in developing and deploying advanced energy technologies."[1]

The second part of the committee's task was to conduct both an operational assessment and a retrospective and prospective technical assessment in the context of the agency's statutorily defined means of achieving its goals "through energy technology projects by—

(A) identifying and promoting revolutionary advances in fundamental and applied sciences;
(B) translating scientific discoveries and cutting-edge inventions into technological innovations; and
(C) accelerating transformational technological advances in areas that industry by itself is not likely to undertake because of technical and financial uncertainty."[2]

The committee's operational assessment considers how ARPA-E is organized, how it selects projects to support, how it partners with performers to manage those projects, how it actively manages projects, and what nontechnical support it provides to projects. The technical assessment outlines how ARPA-E, through its project selection and management, has made progress toward producing commercial products with the potential to transform the energy sector. The committee also considered the value to ARPA-E of developing a framework, processes, and specific systems for the collection of data that will be valuable for continuous improvement of operational processes and can serve as the basis for future self- or external technical and impact assessments.

The scope of this study did not include providing a comprehensive benefit-cost analysis or other review of ARPA-E's value, such as a comparison with other possible uses of federal funding. Such an analysis is infeasible with currently available data. The study scope did include consideration of what lessons learned from the operation of ARPA-E may apply to other DOE programs, as well as factors that Congress should take into account in determining the agency's future.

STUDY METHODOLOGY AND LIMITATIONS

The committee's findings and recommendations are based on both quantitative and qualitative data, including agency data, publicly available data, observations at agency events, presentations by personnel from ARPA-E, DOE, and the Defense Advanced Research Projects Agency (DARPA), case studies of completed awards, consultations with current and former ARPA-E personnel, and consultations with individuals from other programs and offices at DOE. The development of new or transformative energy technologies from initial discovery to broad market deployment typically takes several decades. ARPA-E provides support for projects very early in this process, typically around first translation from scientific discovery to engineering—focusing on ideas at technical readiness levels 2 to 4—with the possibility of leading to a

[1]42 U.S.C. 149 § 16538(c)(1).
[2]42 U.S.C. 149 §16538(c)(2).

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marketable product. Most ARPA-E awards last for about 3 years, much shorter than the decades required to commercialize energy technologies. Unsurprisingly, few data were available for this study regarding ARPA-E's impact on energy technologies or the sector as a whole. Still, 6 years of operation provides data demonstrating the intermediate impacts of ARPA-E's activities. The committee developed its findings and recommendations by analyzing these available data.

DEFINING ORGANIZATIONAL FEATURES OF ARPA-E

Within the Department of Energy (DOE), ARPA-E can be distinguished by its culture, methods, and focused mission and goals. Through the course of its deliberations and analyses of the evidence gathered for this assessment, the committee found that ARPA-E benefits from three defining organizational features:

- The director provides technical and leadership skills that enable and sustain a culture of empowerment.
- ARPA-E's program directors are empowered with the authority, responsibility, and ability to make program- and project-related decisions.
- Active project management is important to ARPA-E.

Collectively, these three features have the potential to contribute to ARPA-E's ability to achieve its intended mission and goals. The absence of these features would not guarantee failure, and their presence does not ensure success. However, these features are important to creating a culture that can enable success.

KEY FINDINGS

Closely linked to the defining organizational features set forth above, the committee developed 18 findings based on the available data and evidence. While all of these findings are necessary for understanding the progress ARPA-E has made toward fulfilling its mission and goals, five stood out to the committee as especially important.

> ***Finding 3-7[3]: ARPA-E selects projects to fund through a multifaceted process that entails evaluating each project's potential to contribute to the achievement of the agency's goals should it be successful.***

Quantitative evidence demonstrates that ARPA-E has instituted a system focused on finding and funding ideas with a high potential for impact on achievement of the agency's goals. The evidence also shows that this system involves a numbers of stages, and that at each stage ARPA-E uses a multifactor process to make decisions regarding applications. This process emphasizes technical comments from internal and external reviewers; applicants' responses to those comments; and a holistic assessment of funding recommendations that considers the technical

[3]The committee's findings and recommendations are numbered according to the chapter and ordering where they appear.

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content of the applications, the potential for impact on achieving agency goals should projects be successful, and nontechnical factors. The process addresses such important issues as portfolio balance, both across technical categories and within the funded program, with an eye to ensuring sufficiently varied approaches. This process is distinguishable from those of some other agencies that make funding decisions based principally or solely on numerical reviewer scores, often utilizing a strict cutoff that does not allow for discretion on the part of the agency or program directors. Strong and consistent evidence indicates that projects selected through ARPA-E's process have the potential to yield measurable outcomes at least as good as, if not better than, those of projects that would have been selected had less discretion been allowed.

Finding 3-8: ARPA-E program directors have wide authority to develop new focused technology programs that are potentially transformative.

The committee consistently found both qualitative and quantitative evidence that ARPA-E's program directors are empowered with wide authority to carry out their responsibilities, including those outlined in the agency's authorizing statute. Program directors create new technologically focused programs through a process that encourages novel ideas with the potential to identify and promote revolutionary advances or translate discoveries into technological innovations. This process involves collaboration and critical review with the agency director, other program directors, and the wider research community. It also encourages the pursuit of ideas overlooked or ignored by other funders, as well as truly novel ideas.

Finding 3-9: ARPA-E program directors actively manage projects through technical research guidance and feedback, regular and frequent assessments of progress made toward stated technical milestones, and revision of milestones in response to new findings and research discoveries.

Throughout a program's life cycle—from review of applications, through award negotiations, to completion of individual projects—program directors engage in active project management. They work closely with performers to create milestones, which can be modified in accordance with what the team learns through the course of its research. Program directors regularly engage with performers to discuss a project's technical approach and collaborate to revise it based on results to date. They work with performers to modify their research approaches, when appropriate, in response to data obtained through the course of research. Such changes can range from minor modifications of protocols, techniques, or project milestones to more significant project restructuring or changes in direction. Program directors even can, and do, recommend personnel changes and work with performers to identify and recruit qualified personnel or subcontractors. They also recommend that the agency terminate funding early when projects repeatedly fail to meet their milestones and appear unlikely to do so in the future.

Collectively, findings 3-7, 3-8, and 3-9 suggest that ARPA-E has thus far maintained its independence from such constituencies as groups seeking funding. Implementation of several of the recommendations presented below, particularly Recommendations 3-1, 4-3, and 4-8, would help ensure that ARPA-E maintains its independence.

Finding 4-2: The projects ARPA-E has funded support its statutory mission and goals.

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Finding 4-3: While 6 years is not long enough to produce observable evidence of widespread deployment of funded technologies, there are clear indications that ARPA-E is making progress toward its statutory mission and goals.

While the full market impacts of the technologies that ARPA-E has funded undoubtedly will not be seen for years, some intermediate outcomes are evident now. Roughly half have published results of their research in peer-reviewed journals, and about 13 percent have obtained patents. One quarter of the supported project teams or technologies have received follow-on funding for continued work. All of these are positive indicators for technologies on a trajectory toward commercialized products. In fact, several are either already commercially available or poised to enter the commercial market.

Two important observations can be derived from these facts. First, there is an inherent tension to be managed by ARPA-E between having a short-term impact on a technology within the 3-year funding timeframe while producing transformational technologies. Second, after 6 years of operation, there exist only about 3 years of completed projects to serve as evidence of progress toward ARPA-E's mission and goals. These two observations speak simultaneously to the need to consider ARPA-E's impact in context and over a duration that is well aligned with the agency's mission and the reality of the market dynamics of energy technologies, and to the need to gather, systematically, more and better data that can be used to discern and monitor mechanisms that may lead to a better understanding of how a technology's full impact is achieved over time.

Reviewing the findings presented above, together will all the findings and evidence gathered and presented for this report, it is evident that assessing ARPA-E at this time is a difficult task. ARPA-E's was expressly created to achieve long-term environmental, security, and competitiveness goals. It was structured to fund and manage research and development (R&D) undertaken by entities other than the agency rather than undertaking its own R&D activities. Because the agency is tasked with seeking out transformational technological advances, it has necessarily utilized novel operational benchmarks to try to accomplish its goals.

Any assessment of the agency at this time will encounter a well-known problem in R&D management: since sufficient time has not passed for outcomes to have become evident, an assessment cannot draw strong conclusions unless the enterprise is in an extreme situation, such as doing very badly. The findings make clear that ARPA-E is not in an extreme situation. The agency is not failing and is not in need of reform. In fact, attempts to reform the agency—such as applying pressure for ARPA-E to show short-term successes rather than focusing on its long-term mission and goals—would pose a significant risk of harming its efforts and chances of achieving its mission and goals.

Nonetheless, the committee is confident that the data obtained and analyzed for this assessment indicate that ARPA-E has grown from a concept into a functioning organization and has made demonstrable progress toward achieving its statutory mandates. Moreover, the committee hopes that this report will provide useful guidance to ARPA-E as it continually assesses its data collection procedures with an eye toward improving operations and supporting future self- and independent evaluations of the agency.

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KEY RECOMMENDATIONS

On the basis of its findings, the committee formulated 14 recommendations intended to help ARPA-E continue to strengthen and build upon its early success. Five of these 14 recommendations stand out as key to positioning the agency for success to fulfill its mission and goals, and are presented here with their supporting findings.

Recommendation 3-1: ARPA-E should preserve its distinctive and flexible management approach that empowers program directors and stresses active project management.

Findings 3-1, 3-2, and 3-3 show how ARPA-E has internalized the principles of an innovative culture, dynamic leadership, and program director autonomy in its organizational structure. Specifically, it is evident that ARPA-E's program directors have been empowered to take risks in project selection in line with the agency's mission; have been given discretion that enables ARPA-E to fund relatively risky projects, with no clear indication that average project performance in the short term is reduced; and continuously engage in active management of ongoing projects, as reflected in the altering of project milestones, budgets, and timelines. These findings highlight the important role of the program directors in supporting ARPA-E's vitality and in enabling the agency to execute its mission and goals.

The committee recommends that ARPA-E strive to preserve this management approach that gives its program directors wide authority to develop new focused technology programs with potential to be transformative and enables them to manage projects actively through technical research guidance and feedback, regular and frequent assessments of progress toward stated milestones, and revision of milestones in response to new findings and research discoveries. This management approach is a defining organizational feature that can contribute to the agency's ability to achieve its statutory mission and goals, and helps to distinguish ARPA-E from other public funding initiatives for energy R&D.

Recommendation 4-8: The ARPA-E director and program directors should develop and implement a framework for measuring and assessing the agency's impact in achieving its mission and goals.

As described in Finding 4-9, ARPA-E is not yet able to assess the full extent to which it has achieved its statutory mission and goals. The agency has in place an extensive data gathering and recordkeeping system at the project level with which to track and monitor internal metrics and facilitate active program management. It has a less extensive system for collecting, tracking, and reporting publicly available high-level innovation metrics such as publications; funding from other sources; and intellectual property information, including disclosures and patents over time. Even if these traditional innovation metrics were available through a more systematic approach to their collection, they could not enable a robust, quantifiable assessment of whether and how ARPA-E's activities have contributed to achieving its statutory mission and goals. Consequently, neither the agency nor any other assessor can at present perform such an assessment. ARPA-E is, however, in a good position to develop a framework for prospectively mapping project-level data from program creation, through project selection and management, to mission success and achievement of goals.

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The development and implementation of such a framework would be very valuable and important for ARPA-E to undertake as soon as practicable, providing the agency with greater ability to demonstrate its value and impact. It is critical that ARPA-E not delay implementation. The longer the agency waits, the more difficult it will be to implement such a framework and the less valuable it will be, and it will become more difficult if not impossible to assess program impacts in a way that allows for meaningful reform in response. The agency could link data from its robust internal database of project-level metrics to program-level goals, including indicators of commercial and noncommercial outcomes over the short and long terms; connect those goals to standard, observable innovation metrics; and then translate those metrics into progress toward achieving the agency-level mission and goals. Such a framework would need to include a system for tracking performers postfunding for at least 10 years, and very likely longer, to capture technologies that are transferred in arms-length transactions along with other ways of observing technology deployment.

At the agency level, ARPA-E already is known for a willingness to assess its structure and operations and experiment with changes aimed at improving both operations and outcomes. Designing and implementing such a framework could place the agency at the forefront of self-evaluation, with the ultimate aim of improving the outcomes of its work. To develop and implement this framework in a way that would best serve the agency, ARPA-E's director and staff would need to be empowered with the autonomy to do so based on their direct experience with running the agency and managing projects.

> **Recommendation 3-3: ARPA-E should reconceptualize its "tech-to-market" program to account for the wide variation in support needed across programs and performers with respect to prospective funding, commercialization, and deployment pathways.**

Finding 3-4 describes how ARPA-E views its "tech-to-market" (T2M) activities as an ongoing experiment, and the challenge of developing such a program may be greater than originally thought. Incumbent energy technologies have long usable life spans. Adequately verifying and validating new energy technologies usually takes decades, and large amounts of capital are required relative to what is necessary in other technology sectors. Still more time is required to develop technologies into commercial products. The roughly 3-year timeframe of an ARPA-E project is too short to expect a technology to move from concept to market.

The value added by ARPA-E's T2M activities varies by project and performer. Some performers consulted during this study, in particular those with established product development and marketing capacity, have not found ARPA-E's current approach for T2M helpful. Other performers, such as academic teams, have found value in the agency's T2M guidance. Given that the agency continually strives to evolve and improve its approach to T2M, the committee encourages further evolution of that approach while cautioning against overexpansion. For example, ARPA-E should consider making full T2M plans optional—encouraging development of these plans by performers most likely to benefit, such as academics—but requiring performers to describe potential product applications if they can prove technological feasibility. It also could provide information or research to performers on critical nontechnical factors that could impact market adoption of future products, such as regulatory risk and other, common risks other than business-market risks.

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Recommendation 4-3: ARPA-E should continue to use processes designed to identify and support unexplored opportunities that hold promise for resulting in transformational technological advances.

Finding 4-4 describes the importance for ARPA-E of seeking high-risk, potentially transformative technologies and overlooked, "off-roadmap" opportunities pursued by neither private firms nor other funding agencies, including other programs and offices within DOE, as a way to position itself to accomplish its mission. ARPA-E's underlying organizational features include encouraging its program directors to seek potentially high-impact projects and recognizing that many of its projects will produce only valuable knowledge, including knowledge of research pathways that should not be pursued further, instead of commercialized products.

Maintaining this focus will be one of the greatest challenges for ARPA-E in the future. It is not guaranteed that ARPA-E will be able to maintain a culture of pursuing high-risk but potentially transformative technologies and research pathways characterized as novel or significantly underexplored as the energy technology landscape evolves. ARPA-E leadership and the secretary of energy should actively work to sustain this culture. ARPA-E should continue to balance its overall portfolio between technologies that appear to have the potential to be transformative and other valuable opportunities that are being ignored.

Recommendation 3-5: The secretary of energy should ensure that other offices and programs within DOE continue to explore and adopt elements of ARPA-E's practices that can improve the department's operations.

Findings 3-1, 3-2, and 3-3 provide details on ARPA-E's program creation and project management. Finding 3-6 supports the positive influence those practices have had on other offices within DOE. To cite a direct example, the Office of Energy Efficiency and Renewable Energy has incorporated several elements of ARPA-E's approach into the management of its programs, including use of a workshop to define a program, use of concept papers to screen funding applicants, and early termination of underperforming projects. While some elements of ARPA-E's approach may be difficult to scale or translate to other programs and offices, there is great benefit in exploring their adaptability and suitability. Of particularly high value would be finding suitable ways to incorporate such key features as term-limited program managers, use of constructive engagement among program directors to sharpen the focus of programs, the degree of operational freedom accorded to program managers, and the risk-taking orientation of programs. Other DOE offices have expressed interest in adopting a number of these features. The secretary of energy should encourage and empower those offices to explore and adopt appropriate practices.

FINAL THOUGHTS

ARPA-E has the ability to make significant contributions to energy R&D that likely would not take place absent the agency's activities. The committee believes that implementation of its recommendations would benefit ARPA-E, and the nation, as the agency continues to evolve and improve its operations in service of its mission and goals. The committee also believes that these recommendations should be helpful to Congress as it considers ARPA-E's future.

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BOX S-1
COMPLETE LIST OF ALL FINDINGS

Findings regarding ARPA-E's Internal Operations:
Culture, People, and Processes (Chapter 3)

Finding 3-1: ARPA-E program directors have been empowered to take risks in project selection in line with the agency's mission.

Finding 3-2: Program director discretion enables ARPA-E to fund relatively risky projects, with no indication that average project performance in the short term is reduced.

Finding 3-3: Program directors are continuously engaged in ongoing projects, as reflected by the altering of project milestones, budgets, and timelines, to help ensure that projects support ARPA-E's mission and goals.

Finding 3-4: ARPA-E considers its "technology-to-market" (T2M) activities to be an ongoing experiment, and the challenge of developing such a program may be greater than originally thought.

Finding 3-5: The program director hiring policies at ARPA-E appear to complement the agency's programmatic timelines. Many projects experience a program director transition, but on average, this transition is not detrimental to project performance.

Finding 3-6: ARPA-E is a positive agent of change in DOE and the federal government, and its best practices are being adopted in some DOE offices. ARPA-E's role as a positive change agent has been facilitated by its outreach and bridge-building efforts with respect to other federal organizations since its formation.

Finding 3-7: ARPA-E selects projects to fund through a multifaceted process that entails evaluating each project's potential to contribute to the achievement of the agency's goals should it be successful.

Finding 3-8: ARPA-E program directors have wide authority to develop new focused technology programs that are potentially transformative.

Finding 3-9: ARPA-E program directors actively manage projects through technical research guidance and feedback, regular and frequent assessments of progress made toward stated technical milestones, and revision of milestones in response to new findings and research discoveries.

Findings regarding Technical Assessment (Chapter 4)

Finding 4-1: ARPA-E has funded research that no other funder was supporting at the time. The results of some of these projects have prompted follow-on funding for various technologies, which are now beginning to enter the commercial market.

Finding 4-2: The projects ARPA-E has funded support its statutory mission and goals.

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Finding 4-3: While 6 years is not long enough to produce observable evidence of widespread deployment of funded technologies, there are clear indications that ARPA-E is making progress toward its statutory mission and goals.

Finding 4-4: One of ARPA-E's strengths is its focus on funding high-risk, potentially transformative technologies and overlooked, "off-roadmap" opportunities pursued by neither private firms nor other funding agencies, including other programs and offices within DOE.

Finding 4-5: Some of the language used by ARPA-E creates an impractical expectation and mission that are not necessarily in the agency's original authorizing statute.

Finding 4-6: The high-touch nature of project management at ARPA-E is a hallmark of the agency and has been praised by performers. That said, quarterly reporting in terms of required written documentation is currently challenging, depending on the technical context. Given that quarterly written reports are offset in time with site visits from program directors and their teams, a project performer may end up having 8–10 direct interactions with ARPA-E per year.

Finding 4-7: Through its projects and programs, ARPA-E is accumulating not only technical knowledge of what is working and has promise, but also potentially very useful information on what does not work that can be an important addition to ARPA-E documentation.

Finding 4-8: ARPA-E is in many cases successfully enhancing the economic and energy security of the United States by funding transformational activities, white space, and feasibility studies to open up new technological directions and evaluate the technical merit of potential directions. However, ARPA-E is doing a poor job of creating awareness of these very real successes while at the same time holding itself to a metric of success that is not aligned with its authorizing statute or fundamentally essential to the energy and economic security of the United States (see Finding 4-5).

Finding 4-9: ARPA-E is not yet able to assess the full extent to which it has achieved its statutory mission and goals. However, it is in a good position to develop a framework for prospectively mapping data on project selection and management to mission success and goal achievement.

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BOX S-2
COMPLETE LIST OF ALL RECOMMENDATIONS

Recommendations regarding ARPA-E's Internal Operations: Culture, People, and Processes (Chapter 3)

Recommendation 3-1: ARPA-E should preserve its distinctive and flexible management approach that empowers program directors and stresses active project management.

Recommendation 3-2: ARPA-E should continue to hire exceptional program directors and empower them to create programs and manage projects.

Recommendation 3-3: ARPA-E should reconceptualize its "technology-to-market" program to account for the wide variation in support needed across programs and performers with respect to prospective funding, commercialization, and deployment pathways.

Recommendation 3-4: ARPA-E should continue its practice of hiring program directors for 3-year terms, allowing for one, term-limited extension when necessary to complete implementation of a new program or for other reasons determined by the ARPA-E director.

Recommendation 3-5: The secretary of energy should ensure that other offices and programs within DOE continue to explore and adopt elements of ARPA-E's practices that can improve the department's operations.

Recommendation 3-6: ARPA-E and DOE should provide incentives to encourage more interaction between other DOE program offices and ARPA-E, which could potentially help reduce DOE's bureaucratic culture.

Recommendations regarding Technical Assessment (Chapter 4)

Recommendation 4-1: Policy makers should recognize that there is limited evidence to date on transformational impacts emerging from ARPA-E, given the short time since ARPA-E began.

Recommendation 4-2: The director of ARPA-E should continue to promote and maintain a high-risk culture within the agency. Means to this end include periodic reassessment to ensure that the principles that drive support for high-risk projects are being maintained.

Recommendation 4-3: ARPA-E should continue to use processes designed to identify and support unexplored opportunities that hold promise for resulting in transformational technological advances.

Recommendation 4-4: ARPA-E should be careful not to misinterpret or extend its interpretation of its original authorizing statute, whose careful language is appropriate to the agency's mission and goals.

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Recommendation 4-5: ARPA-E should consider streamlining the quarterly reporting process so it consists of presentations to the program directors and their teams, with only the fourth-quarter/annual report providing full written details. Doing so would allow the agency to maintain close contact with performers while relieving some of the burdens on them.

Recommendation 4-6: ARPA-E program directors should compile a document or other repository of lessons learned on all projects, including both positive and negative outcomes.

Recommendation 4-7: ARPA-E should increase and improve its communication for non-technical audiences, including the impact of its activities, the diversity of appropriate metrics to judge the success of individual projects and programs, and the fact that no single metric is appropriate for this purpose.

Recommendation 4-8: The ARPA-E director and program directors should develop and implement a framework for measuring and assessing the agency's impact in achieving its mission and goals.

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1

Introduction

When the U.S. Congress authorized creation of the Advanced Research Projects Agency-Energy (ARPA-E) within the U.S. Department of Energy (DOE), it mandated that the secretary of energy ask the National Academy of Sciences to assess how well the agency was achieving its statutory mission and goals. ARPA-E's authorizing statute states that its mission is "to overcome long-term and high-risk technology barriers in the development of energy technologies,"[1] and its goals are

> "(A) to enhance the economic and energy security of the United States through the development of energy technologies that result in—
> (i) reductions of imports of energy from foreign sources;
> (ii) reductions of energy-related emissions, including greenhouse gases; and
> (iii) improvement in the energy efficiency of all economic sectors; and
> (B) to ensure that the United States maintains a technological lead in developing and deploying advanced energy technologies."[2]

ARPA-E began operating in 2009, and as requested by the Congress, the National Academy of Sciences convened an ad hoc study committee to undertake this assessment starting in 2015, after 6 years of agency operations. The purpose of this study was to provide the information requested by the Congress as input to its consideration of the future of ARPA-E, to summarize lessons learned that may apply to the operations of other DOE programs,[3] and to provide ARPA-E leadership with information it can utilize as the agency continues to evolve and seeks to improve its efficacy and impact.

STATEMENT OF TASK

ARPA-E was originally conceived in a recommendation from a previous study of the National Academies (NAS et al., 2007). The statutory language mandating this assessment

[1] 42 U.S.C. § 16538(b). This subsection is labeled "ESTABLISHMENT," but its second clause appears to state Congress's intended mission for ARPA-E.
[2] 42 U.S.C. § 16538(c).
[3] 42 U.S.C. § 165381(l).

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requested a review of the agency's methods, its success in fostering transformational innovation, and the adequacy of its resources. Those topics are reflected in the statement of task for this study (see Box 1-1).

BOX 1-1
Statement of Task

The Advanced Research Projects Agency-Energy (ARPA-E) was established in 2009 for the stated purpose of funding energy technology projects by "identifying and promoting revolutionary advances in fundamental and applied sciences; translating scientific discoveries and cutting-edge inventions into technological innovations; and accelerating transformational technological advances in areas that industry by itself is not likely to undertake because of technical and financial uncertainty."

An *ad hoc* committee will review and evaluate the progress that ARPA-E has made toward achieving its goals. The committee will develop a methodology and framework for an operational assessment as well as a retrospective and technical assessment of ARPA-E and then conduct both. The operational assessment will appraise the appropriateness and effectiveness of ARPA-E's structure to position it to achieve its mission and goals. Specifically, the committee will:

- Evaluate ARPA-E's methods and procedures to develop and evaluate its portfolio of activities;
- Examine appropriateness and effectiveness of ARPA-E programs to provide awardees with non-technical assistance such as practical financial, business, and marketing skills;
- Assess ARPA-E's recruiting and hiring procedures to attract and retain qualified key personnel;
- Examine the processes, deliverables, and metrics used to assess the short and long term success of ARPA-E programs;
- Assess ARPA-E's coordination with other Federal agencies and alignment with long-term DOE objectives;
- Evaluate the success of the focused technology programs to spur formation of new communities of researchers in specific fields;
- Provide guidance for strengthening the agency's structure, operations, and procedures;
- Evaluate, to the extent possible and appropriate, ARPA-E's success at implementing successful practices and ideas utilized by the Defense Advanced Research Projects Agency (DARPA), including innovative contracting practices; and
- Reflect, as appropriate, on the role of ARPA-E, DOE, and others in facilitating the culture necessary for ARPA-E to achieve its mission.

The committee's retrospective assessment and technical evaluation will describe the most significant accomplishments and/or impacts of the ARPA-E program to date and any unique features of the program that may have contributed to these accomplishments, and consider how well ARPA-E's activities have supported the agency's goals. Specifically, the committee will:

- Analyze specific focused technology programs and/or awardee projects to determine whether ARPA-E is focused on truly "transformational" technologies;
- Examine funded projects to assess and whether ARPA-E solicitations attract the best and brightest to the relevant program areas;

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- Identify where ARPA-E projects have made an important difference; and
- Assess performance of the portfolio of awards and evaluate whether and how much the award portfolio has helped ARPA-E achieve its goals.

Developing new energy technologies often requires several decades, while ARPA-E has operated for six years. This will likely limit the quantity and quality of available data and other evidence of long-term outcomes such as commercialization of new technologies. If and where the committee finds a paucity of data or other evidence, the committee will assess progress to date and also identify the most valuable data and information that ARPA-E could gather going forward.

The committee will issue a final report detailing its findings, conclusions, and recommendations, including suggestions for improvements in ARPA-E, lessons learned from the operation of ARPA-E that may apply to other DOE programs, and factors that Congress should take into consideration in determining the future of ARPA-E.

STUDY SCOPE

To operationalize the statement of task for this study, the ad hoc committee posed three broad questions that this report is intended to answer:

- What qualitative and quantitative standards are appropriate for assessing ARPA-E's performance?
- To what extent are ARPA-E's organization, operational methods, and personnel practices positioning it to accomplish its mission and goals as established by the Congress?
- What impacts has ARPA-E had on its awardees and on the nation's energy technology innovation system?

In attempting to answer these questions, the committee had to take several caveats into account:

- ARPA-E's performance has been affected by external factors, such as the length of time that elapsed while awaiting Senate confirmation of both its first and second directors.
- The 6 years of ARPA-E operations provides insufficient data to enable a full assessment of potentially transformational research whose impact likely will not be fully observable until years or decades in the future.
- A number of important terms in the statement of task—such as "cutting-edge inventions," "revolutionary advances," "qualified key personnel," and "transformational technological advances"—are intrinsically subjective, difficult to define, and even more difficult to measure.

STUDY APPROACH

ARPA-E's authorizing legislation is not specific as to how or to what standards the agency's operations and performance were to be measured. Accordingly, the committee elected to apply

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metrics traditionally used in the study of innovation in attempting to measure intermediate outcomes of the work completed under projects funded by ARPA-E.

The committee approached its task by utilizing both quantitative and qualitative methods. To carry out the assessment, it formed four subgroups with a number of committee members and National Academies staff participating in more than one subgroup. Some data gathering and processing was performed by independent consultants. The Internal Operations Qualitative Data Team collected and analyzed qualitative data, including information gathered during interviews with current and former ARPA-E personnel and DOE officials and discussions with stakeholders at agency events, such as program kickoffs and interim meetings. The Case Study Team conducted three types of case studies (a focused program, a portfolio of energy storage projects, and individual projects). The Internal Operations Quantitative Data Team accessed internal, proprietary ARPA-E data and reported aggregated findings. Finally, the External Quantitative Data Team obtained data from external sources, such as the U.S. Patent and Trademark Office's (USPTO) patent database and publications. (See Appendix B for more details on the data and methods used in this report.) Using the statement of task as the point of departure, the subgroups considered the evidence that became available through their research activities. Their deliberations on this evidence led to provisional findings that were summarized and presented to the full committee, which discussed, debated, and compared them. This process went through a number of iterations, leading to final findings and recommendations based on those findings.

The first ARPA-E awards were made in October 2009 for projects of 3 years' duration, meaning that any external impacts from these first-generation projects after ARPA-E funding had ended would have begun to manifest only during the 3 years preceding the start of this study. By contrast, the development of new energy technologies usually requires decades of effort, and decades also must usually elapse before it becomes evident that innovations are truly transformative. It is likely, therefore, that any external impact of more recently initiated projects, which represent the bulk of ARPA-E's portfolio, will not be observable for some years. Consequently, the committee's findings are best regarded as early assessments based on the evidence available over a relatively short timeframe. While more data and more time for analysis may result in more understanding, the committee is confident that the findings and recommendations presented in this report are more than sufficient for use by the Congress in determining ARPA-E's future, and will be of value to ARPA-E as it continues to evolve and improve its operations.

ORGANIZATION OF THE REPORT

Chapter 2 of this report presents an overview of ARPA-E's genesis, structure, and operations; its congressional mandate and funding; and the results of previous agency audits and oversight initiatives. Chapter 3 provides details of the committee's operational assessment of ARPA-E's performance as an organization, its operational methods, and its personnel practices. Chapter 4 presents the committee's technical assessment of the extent to which the projects ARPA-E has funded have contributed to the agency's achievement of its statutory mission and goals, to the extent this can be ascertained from the relatively brief experience base accumulated since the agency began its operations. The report also includes six appendixes: Appendix A provides biographical information on the committee members; Appendix B summarizes the various methodologies used in this assessment; Appendix C contains the full text of the 10 case studies developed as input for this assessment; Appendix D provides a glossary of acronyms and

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abbreviations used in this report; Appendix E contains the committee's formal request for data made to ARPA-E and the agency's official response; and Appendix F includes the white papers prepared by external consultants detailing their data analyses.

REFERENCE

NAS (National Academy of Sciences), NAE (National Academy of Engineering), and IOM (Institute of Medicine). 2007. *Rising above the gathering storm: Energizing and employing America for a brighter economic future*. Washington, DC: The National Academies Press.

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2

Overview of ARPA-E

This chapter provides a descriptive overview of ARPA-E, starting with its origins and attributes. It then describes the agency's organizational structure and presents sufficient detail on its operations and procedures to enable readers not familiar with the agency to better understand the assessment presented in Chapters 3 and 4.

ORIGINS

ARPA-E was recommended to Congress in the 2005 National Academies report *Rising above the Gathering Storm: Energizing and Employing America for a Bright Economic Future.* (NAS et al., 2007). The purpose of that report was to recommend specific federal government actions with the potential to maintain and expand U.S. competitiveness and to detail concrete steps for acting on those recommendations. ARPA-E grew out of the following recommendation:

> The federal government should create a DARPA [Defense Advanced Research Projects Agency]-like organization within the Department of Energy called the Advanced Research Projects Agency-Energy (ARPA-E) that reports to the under secretary for science and is charged with sponsoring specific R&D programs to meet the nation's long-term energy challenges....ARPA-E would provide an opportunity for creative "out-of-the-box" transformational research that could lead to new ways of fueling the nation and its economy, as opposed to incremental research on ideas that have already been developed.…Like DARPA, ARPA-E would have a very small staff, would perform no R&D itself, would turn over its staff every 3 to 4 years, and would have the same personnel and contracting freedoms granted to DARPA (NAS et al., 2007, p. 152).

It was further recommended that ARPA-E be funded at an initial level of $300 million in its first year, rising to $1.0 billion per year over a 5- to 6-year timeframe.

In 2007, the 110th Congress enacted the America COMPETES Act ("the Act"), which implemented a number of the *Gathering Storm*'s recommendations, including the creation of ARPA-E (Gonzalez, 2015). The 2007 Act was subsequently superseded by the America COMPETES Reauthorization Act of 2010, which incorporated much of the original language of

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the 2007 Act but introduced some modifications, including the language authorizing ARPA-E.[1] In 2009, ARPA-E received its first appropriated funds and commenced operations.[2]

ATTRIBUTES

The Act charters ARPA-E to look much like DARPA. It tasks ARPA-E with funding high-risk, potentially high-return research, to translate "scientific discoveries and cutting-edge inventions into technological innovations,"[3] and leaves the agency free to support research into any type of technology or fuel that supports its mission. To enable the agency to be well positioned to identify and support this kind of research, the Act exempts it from many federal rules and regulations. The Act also deliberately attempts to structure the agency to be different from other Department of Energy (DOE) offices or programs,[4] especially with regard to its level of flexibility, and to position it to be relatively autonomous within the department. For example, the Act provides funding separate from that for ongoing DOE programs and standing offices, gives the director considerable control over the agency, and seeks to make it separate from the rest of the DOE hierarchy. The director is to report directly to the secretary of energy rather than another office.[5] ARPA-E's budget request and congressional appropriations are to be made "separate and distinct from the rest" of the DOE budget, and without specification regarding how the appropriation should be allocated.[6]

To run ARPA-E and make investments in projects, the director is mandated to hire program directors. These individuals are to serve for a 3-year term that can be renewed, and are given a great deal of autonomy and flexibility in establishing and managing agency programs. The Act also empowers the program directors with significant discretion in recommending projects for funding (as opposed to strict reviewer scoring) and assigns to them the authority and obligation to recommend that the director terminate projects that fail to meet expectations. Preparing technologies for eventual transfer from laboratory to market is a key element of ARPA-E's mission (see below), termed "technology-to-market," or "T2M." ARPA-E project teams prepare a Technology-to-Market Plan, with agency staff from the Technology-to-Market Program assisting in the plan's development and implementation. Fairly or not, ARPA-E is sometimes compared and contrasted with DOE's Office of Energy Efficiency and Renewable Energy (EERE), a much larger research organization with 700 employees, hundreds of contractors, and seven field offices (Ling, 2013). Reflecting the mandate extended to ARPA-E by Congress to enable it to fulfill its mission, the agency features several important structural characteristics that differ from those of most other federal research funding organizations. Figure 2-1 provides a high-level schematic of those characteristics and key operational features of ARPA-E. Each of those is described in this chapter.

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[1]P.L. 111–358.
[2]The American Recovery and Reinvestment Act of 2009 provided an initial $400 million to fund the establishment of ARPA-E.
[3]42 U.S.C. 16538(c)(2)(B) (2017).
[4]The term "program" has a very specific meaning for ARPA-E that is different from that in the rest of DOE. For ARPA-E, a program refers to a specific focused technology funding opportunity and the research projects funded under it. These always have a narrow, defined scope, limited duration, and no permanent staff. Programs in the rest of the department can refer to an ongoing activity of indefinite duration, with a scope that can be broad and may change over time, has long-term staff, and may or may not provide funding for research activities.
[5]42 U.S.C. § 16538(d).
[6]42 U.S.C. § 16538(n)(3).

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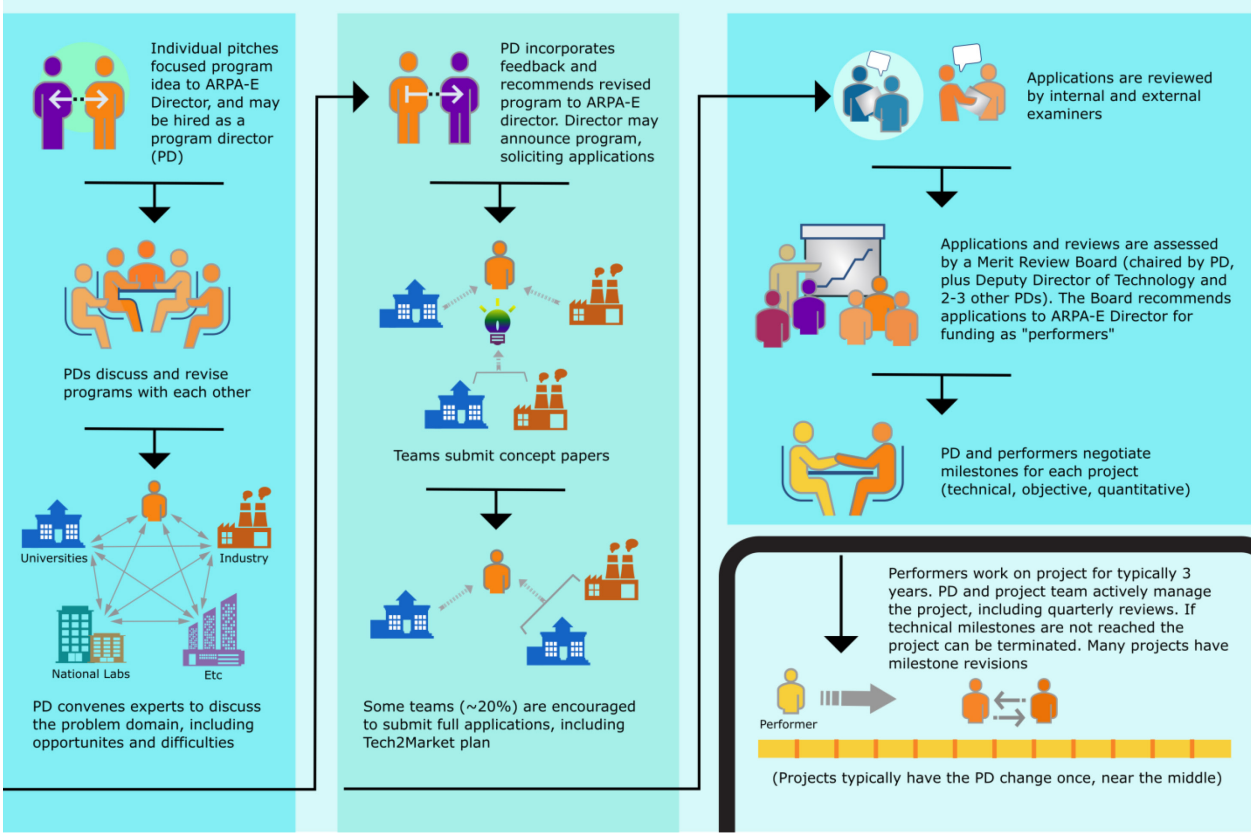

FIGURE 2-1 Schematic of ARPA-E's internal process for program creation, project selection, and performer management.

Although ARPA-E is not the first federal organization tasked with supporting high-risk, potentially high-reward research or the first government entity intended to emulate DARPA, it enjoys statutory and resource advantages not available to any of its antecedents other than DARPA itself. For example, DOE operated a small organization dedicated to novel, high-risk energy research between 1977 and 2000, but this organization—the Advanced Energy Project Division (AEP)—was firmly embedded in the DOE structure, fully subject to federal civil service requirements, and ultimately unable to achieve "transformational" results (DOE, 1999).[7] The Homeland Security Act of 2002 created the Homeland Security Advanced Research Projects Agency (HSARPA) to support "cutting-edge research" aimed at developing "revolutionary changes in technologies, new capabilities and threat and risk assessments" related to homeland security. HSARPA's funding has been limited compared with that of DARPA (in fiscal year [FY] 2007, for example, $38 million compared with $3.1 billion for DARPA), and for most of its existence the Department of Homeland Security has ensured that its projects involve conventional research and development (R&D) with moderate risk.[8]

[7]In the mid-1990s, AEP was operating under annual budgets of $10–11 million. In 1995, it was absorbed into DOE's Computational and Technology Research Program. DOE began ramping down AEP's funding in fiscal year (FY) 1998, requesting only $3 million in its FY 1999 budget, directing the cancellation of several projects, and barring the initiation of "new novel energy-related concepts."

[8]A 2007 analysis found that while Congress had provided HSARPA with a strong and flexible mandate modeled on DARPA, "HSARPA has never been adequately utilized or implemented....HSARPA was never allowed autonomy

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Agency Mission and Goals

Congress statutorily defined ARPA-E's mission as to "overcome the long-term and high-risk technology barriers in the development of energy technologies."[9] The agency's basic statutory goals are to develop technologies that reduce imports of fossil fuel, reduce energy-related emissions, improve energy efficiency in all economic sectors, and ensure that the United States maintains a technological lead in the development and deployment of advanced energy technologies.[10] Additionally, the statute directs ARPA-E to pursue these objectives through particular means:

- identifying and promoting revolutionary advances in fundamental and applied sciences;
- translating scientific discoveries and cutting-edge inventions into technological innovations; and
- accelerating transformational technological advances in areas industry is unlikely to undertake.[11]

The director of ARPA-E is responsible for achieving the agency's statutory goals through targeted acceleration of "novel early-stage energy research with possible technology applications" and "advanced manufacturing processes for the domestic manufacturing of novel energy technologies."[12] The Act emphasizes that ARPA-E is expected to pursue those research technology themes and specific ideas that industry is not likely to undertake by itself.[13]

Personnel Authority

ARPA-E's director is authorized to hire up to 120 "scientific, engineering, and professional personnel without regard to the civil service laws."[14] The director may set pay levels up to Level II of the Office of Personnel Management's Executive Schedule (EX-II), again without regard to the civil service laws.[15] Additional payments may be made within limitations.[16] This authority is meant to empower ARPA-E's director to hire scientists and engineers to serve as program directors quickly and to attract talented individuals. As noted above, use of this hiring authority for program directors is limited to a 3-year appointment, which may be renewed. This provision ensures that program directors pass through ARPA-E with the intent of executing

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and flexibility and instead was closely controlled by a budget and policy bureaucracy within the S&T Directorate that limited HSARPA's funding and effectively made all R&D investment and award decisions." Testimony of William B. Bonvillian, U.S. Congress, Subcommittee on Energy and Environment, Committee on Science and Technology, *Establishing the Advanced Research Projects Agency—Energy*, Hearing, 110th Cong., 2d sess. (April 26, 2007).

[9] 42 U.S.C. § 16538(b).

[10] 42 U.S.C. § 16538(c).

[11] 42 U.S.C. § 16538(c)(2).

[12] 42 U.S.C. § 16538(e)(3)(A) and (C).

[13] 42 U.S.C. § 16538(c)(2)(C).

[14] 42 U.S.C. § 16538(g)(3)(A)(i).

[15] 42 U.S.C. § 16538(g)(3)(A)(ii).

[16] The extra payment cannot exceed the least of three amounts: (1) $25,000, (2) 25 percent of the employee's base rate of pay, and (3) the limitation amount applicable in a given calendar year pursuant to 5 U.S.C. § 5307(a)(1). That section prohibits payments that, when added to the base amount, would exceed the Office of Personnel Management's Executive Schedule Level I (EX-1), which in 2016 was $205,700. 42 U.S.C. § 16538(g)(3)(A)(iii).

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technically challenging projects during their tenure, and that new talent and ideas circulate through the agency (H. Rep. 110-289, 2007).

Additionally, the secretary of energy, or the director of ARPA-E "serving as agent of the Secretary," may contract with private recruiting firms to hire "qualified technical staff."[17] The director is authorized to use "all authorities in existence on August 9, 2007" provided to the secretary of energy to hire administrative, financial, and clerical staff.[18]

Powers Vested in Program Directors

Similar to DARPA program managers, ARPA-E program directors are accorded wide latitude in identifying research themes; creating new programs; making funding recommendations to the director; supervising projects; identifying commercial opportunities; and, when necessary, terminating projects.[19] Program directors are expected to identify "innovative cost-sharing arrangements" for ARPA-E projects (albeit subject to the limitations established by federal cost-sharing regulations) and to help performers identify "mechanisms for commercial applications" of successful energy technology development projects, including partnerships between awardees and commercial entities.[20]

Institutional Autonomy

ARPA-E's institutional autonomy is one of the agency's most notable attributes. While the *Gathering Storm* recommendation suggests housing ARPA-E within what was then DOE's Office of Science, Congress decided to make it an autonomous agency within DOE, outside of the departmental bureaucracy (H. Rep. 110-289, 2007). The director is appointed by the President, with the advice and consent of the Senate, and reports directly to the secretary of energy.[21] No other programs within DOE are to report to the director of ARPA-E, a provision that prevents the director from simultaneously heading another office or program within the department (Stine, 2009).[22] DOE's budget request for ARPA-E is to be "separate and distinct" from the rest of its budget, and congressional appropriations for the Energy Transformation Acceleration Fund administered by ARPA-E are likewise to be "separate and distinct" from the remainder of the department's budget.[23] As of this writing, ARPA-E is even physically separate from the rest of DOE, with offices in a different building in Washington, DC.

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[17]42 U.S.C. § 16538(g)(3)(D).
[18]42 U.S.C. § 16538(g)(3)(C).
[19]42 U.S.C. § 16538(g)(2)(B).
[20]42 U.S.C. § 16538(g)(2)(v)-(vii). Federal cost-sharing requirements for research contracts are set forth in 2 C.F.R. § 200.306.
[21]42 U.S.C. § 16538(d)(1) and (3).
[22]42 U.S.C. § 16538(d)(4).
[23]42 U.S.C. § 16538(n)(3). ARPA-E's director "to the maximum extent practicable" is to ensure that the agency's programs are coordinated with, and do not duplicate, efforts of programs and laboratories within DOE and other relevant research agencies. The director of ARPA-E may, "to the extent appropriate," coordinate technology transfer efforts with DOE's Technology Transfer Coordinator. 42 U.S.C. §16538(i)(1) and (2). DOE's technology transfer coordinator advises the secretary "on all matters relating to technology transfer and commercialization." 42 U.S.C. § 16391.

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Program Termination

Since ARPA-E's core mission is to fund "high-risk" projects, the drafters of its enabling legislation clearly contemplated that some of the projects it funded would prove unable to meet their targets. Consequently, ARPA-E's director is responsible for "terminating programs carried out under this section that are not achieving the goals of the programs."[24] Program directors are responsible for "recommending program restructure or termination of partnerships between awardees and commercial entities."[25] The Conference Report on the 2007 America COMPETES Act states:

> Similar to the Defense Advanced Research Projects Agency the Director is to establish and monitor milestones, initiate research projects quickly, and just as quickly terminate or restructure projects if such milestones are not achieved (H. Rep. 110-289, 2007).

Federal Funding of ARPA-E

As indicated in Table 2-1, ARPA-E has never been funded at the scale or level of resources envisioned by the committee that produced the *Gathering Storm* report. Nevertheless, it has funded more than 400 projects that it has regarded as potentially transformational. As noted above, ARPA-E began operations in 2009, when the Omnibus Appropriations Act of 2009 provided $15 million in funding, augmented in that year by $400 million in special funding appropriated from the American Recovery and Reinvestment Act of 2009 (ARRA, also commonly known as "the Stimulus")[26] (ARPA-E, 2011b). Thereafter, ARPA-E's annual appropriations were provided under the annual Energy and Water Development and Related Agencies Appropriations Act, generally at the level of $280 million per fiscal year[27] (Gonzalez, 2015).

STRUCTURE AND OPERATIONS

Agency Establishment

Although ARPA-E was authorized by the America COMPETES Act in 2007, it was not funded until 2009. DOE staff estimated it would take approximately 1 year for ARPA-E to become operational. DOE leadership pushed for a more aggressive timetable that included simultaneously undertaking a number of tasks required to establish the agency that would otherwise have been done serially. These tasks included hiring a director and key personnel, and drafting solicitations for industry and university R&D proposals (Leopold, 2009).

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[24] 42 U.S.C. § 16538(e)(4).
[25] 42 U.S.C. § 16538(g)(2)(B)(viii).
[26] The Omnibus Appropriations Act of 2009 provided $15 million for ARPA-E in its Science appropriation. The Energy and Water Development and Related Agencies Appropriations Act of 2010 transferred the $15 million to ARPA-E.
[27] In 2013, the budget exercise known as "sequestration" and enacted recessions reduced the appropriated amount to $251 million.

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TABLE 2-1 Recommended Funding Levels (in millions of dollars) for ARPA-E versus Authorizations and Appropriations, 2007–2016

		Authorizations		
Fiscal Year	NAS (2007) Recommendation	America COMPETES 2007	America COMPETES Reauthorization 2010	Appropriations
2007	300	—	—	—
2008	500	300	—	—
2009	700	"such sums"	—	415*
2010	900	"such sums"	—	—
2011	1000	—	300	180
2012	1000	—	306	275
2013	1000	—	312	251
2014	1000	—	—	280
2015	1000	—	—	280
2016	1000	—	—	291
2017	1000	—	—	306

*$15 million in regular appropriations and $400 million in one-time funding pursuant to the ARRA.

The initial hires had experience with energy technology start-ups and venture capital, and were chiefly responsible for building the agency and commencing operations until the Senate confirmed the agency's first director, Arun Majumdar, in October 2009. Early agency personnel said that building the agency from scratch under the aegis of the America COMPETES Act's special authorities allowed it to exist outside of the normal "layers of bureaucracy." Although modeling the new agency on DARPA was not taken as a given, they eventually decided to look to DARPA as a model for many of ARPA-E's structural features and operational practices. Zan Alexander, a former DARPA deputy director, served as a consultant to ARPA-E, and her experience facilitated the adoption of a number of DARPA practices (Marks, 2014).

A number of key characteristics of ARPA-E have been noted as guiding the agency's creation and as essential to its carrying out its mission:

- The agency must be structured to support risk taking as opposed to the risk avoidance that commonly characterizes federal agencies.
- The agency must be able to recruit world-class talent, which in turn requires empowerment of program directors to initiate and run programs of their own creation.
- ARPA-E personnel should normally leave the agency after 3 years.
- The agency's culture should be characterized by "constructive challenge," with each program director's program being subject to scrutiny by other program directors.
- The agency's budget request should remain at a general level, rather than being broken down into multiple line items, thus preserving ARPA-E's discretion in seeking to fund potentially transformational technologies[28] (Danielson, 2015; Orr, 2015).

[28]Under Secretary of Energy for Science and Energy Franklin Orr observes that outside of ARPA-E, DOE undergoes "deep scrutiny" of its budgets by Congress and the Office of Management and Budget (OMB), which probe "very far down into budget line items." He comments that "ARPA-E avoids all of that," and that Congress and OMB are "not normally willing to do that."

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ARPA-E made its first Funding Opportunity Announcement (FOA) in May 2009. In response, the new agency received 3,700 concept papers. From these, it encouraged 334 full applications, which were reviewed by two sets of panels of external reviewers. Based on these reviews and a rigorous selection process, ARPA-E selected 37 projects for funding. The first awards were made in October 2009, 6 months after the agency had received its initial appropriated funds (Lawrence and Abramson, 2014). Awards were made by January 15, 2010, for 35 of the 37 selected projects, a speed that "has now set records within the DOE" (Majumdar, 2010).

Arun Majumdar stated that his initial challenges were threefold: developing the external relationships crucial to the agency's success, creating a new government organization, and launching the right projects and demonstrating results (Lawrence and Abramson, 2014). Meeting these challenges entailed three tasks:

- **Outreach**—Majumdar "reached out to key people in the Department of Energy," established an advisory committee of energy experts, established relationships with other government agencies to identify potential synergies, and convened a meeting of stakeholders in Washington, DC.
- **Organization building**—Majumdar prioritized hiring the most talented individuals and establishing a culture in which they could thrive. Emphasis was placed on engaging in open dialogue, challenging ideas and proposals, and empowering individuals while also holding them accountable.
- **Project selection**—ARPA-E's early funded projects focused on themes that included extremely efficient photovoltaic solar collectors, batteries for transportation, wind turbines, and geothermal energy (Lawrence and Abramson, 2014).

Majumdar has commented on the ease of creating new processes and establishing culture at a new agency relative to attempting to change an existing organization. This process was undertaken at a rapid pace that felt like "building the plane while we are flying it." He also believes this rapid pace helped establish a culture featuring an attitude of accomplishing great things and a sense of urgency (Lawrence and Abramson, 2014). Early program directors corroborate this view, stating that they entered an environment with no existing programs and thus no baseline, and that early leadership was focused on hiring the best and the brightest talent willing to join ARPA-E and then providing them with autonomy and empowerment to identify the most critical and important problems to solve.

The first generation of ARPA-E programs reflected the "blue sky" character of the agency's early days. Over time, as successive programs came into existence, a baseline was created, and subsequent program directors were hired with consideration of their specific expertise in broad thematic areas the agency had identified as strategic.[29]

[29]Personal consultation with Ilan Gur, former ARPA-E Program Director, founder and director of Cyclotron Road at Lawrence Berkeley National Laboratory (September 22, 2015).

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Organizational Framework and Staffing

ARPA-E's structure and operational practices generally resemble those of DARPA, albeit on a smaller scale[30] (Bonvillian and van Atta, 2011). Like DARPA, ARPA-E has a "flat," three-level organizational structure, as shown in Figure 2-2. Its current staff consists of a director, 2 advisors to the director, 3 deputy directors, and 16 program directors, plus 4 fellows; 15 acquisitions, budget, external affairs, and legal staff; and 13 T2M advisors who work with performers to develop and implement commercialization strategies. A number of contractors provide back-office support in the areas of communications, information technology (IT), administration, and contracting support. ARPA-E also utilizes systems engineering and technical assistance (SETA) contractors, who play a large role in assisting program directors with the active management of awards.

ARPA-E has adopted many DARPA practices, including empowerment of program directors, a streamlined project approval process, hands-on project management, use of special hiring authority to build a high-quality human infrastructure, and maintenance of institutional autonomy. Since 2014 it has administered the government contracting process itself using its own contracting staff. This approach enables the agency to hand-pick its procurement staff; act more quickly in such matters as creating contracts and cooperative agreements; and, when appropriate, act flexibly and take strategic risks. ARPA-E has introduced new institutional arrangements, such as the creation of its internal T2M program (reflecting the reality that, unlike DARPA awardees, ARPA-E performers do not sell products primarily into a single-stream procurement system) and a research fellows program to enhance its in-house scientific and technical expertise. Figure 2-3 illustrates how ARPA-E has borrowed from and how it departs from the DARPA model.

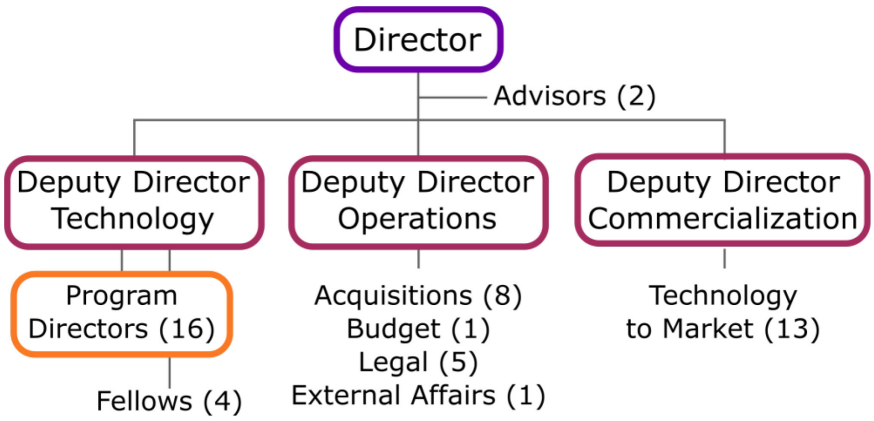

FIGURE 2-2 Organizational chart of ARPA-E in 2016.

[30]ARPA-E's original staff included a former DARPA program manager and an experienced DARPA advisor and performer.

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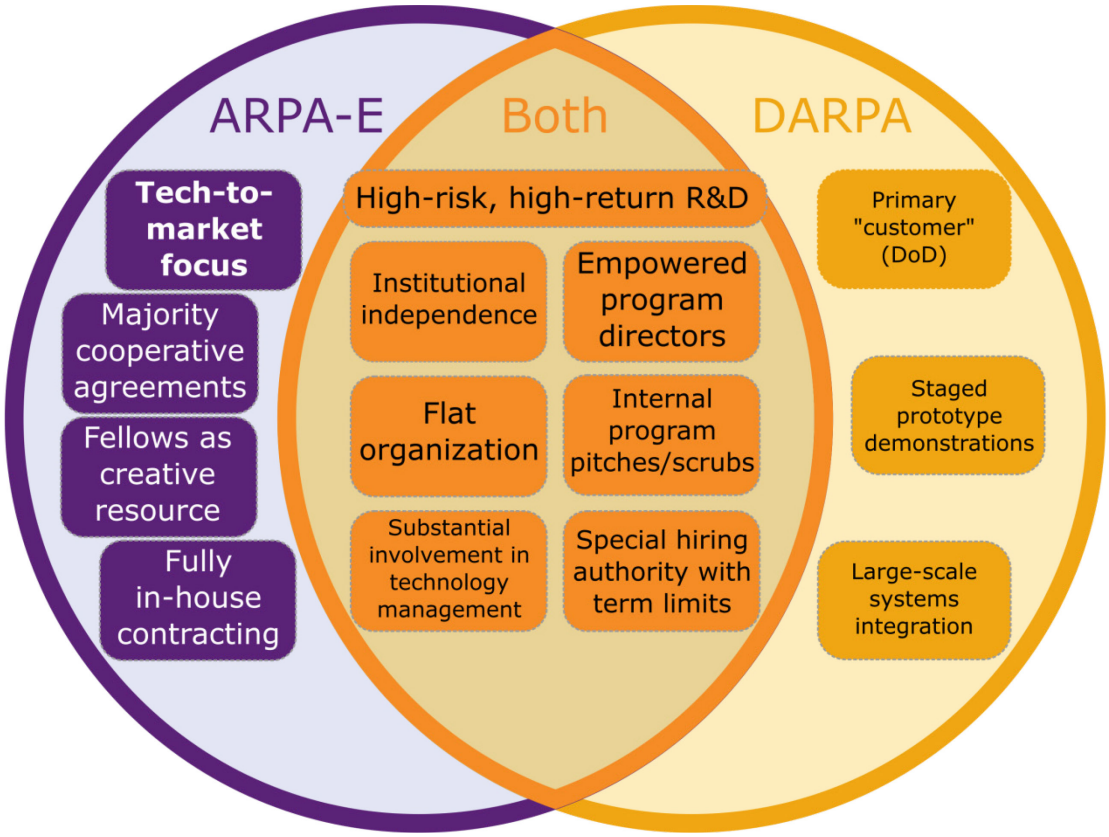

FIGURE 2-3 ARPA-E's depiction of how it has built itself on a foundation modeled after DARPA.
NOTE: DoD = U.S. Department of Defense; R&D = research and development.
SOURCE: ARPA-E, 2015a.

Program Creation

As of the time of this study, new programs appear to arise almost solely because a prospective program director pitches the idea as part of his or her interview for the position. Once a program and its program director are accepted, ARPA-E begins a new program with a "deep dive"—a comprehensive exploration of an energy-related theme aimed at identifying individual topics that represent potential projects for the development of technologies that would enable the agency to achieve one or more of its goals. The objective of the exercise is to identify technology "white spaces" not likely to be addressed by the private sector or by other federal research programs. These white spaces can be of at least two kinds, as shown in Figure 2-4. First, a white space can be a gap in the funding pipeline of all government and private R&D funding (e.g., no funding available for a specific technology at technology readiness level [TRL] 3). ARPA-E funding can move in to address this gap, filling the white space. Second, white space can be a capability just beyond the frontier of what is currently technically possible, which ARPA-E identifies as a strategic need. ARPA-E can attempt to push this frontier by giving directed funding for projects at the frontier.

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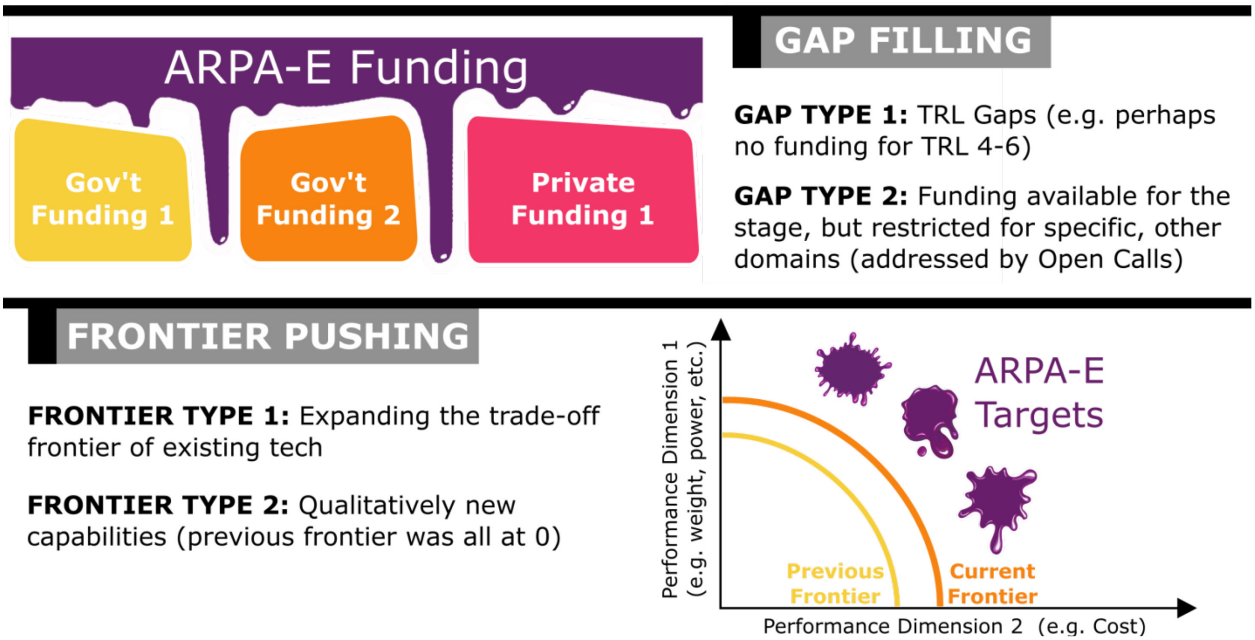

FIGURE 2-4 Schematic of ARPA-E's "white space" strategy.
NOTE: TRL = technology readiness level.

ARPA-E technical staff review the scientific literature, conduct site visits (universities, companies), commission external studies, attend conferences, and participate in webinars to identify such areas, examine the current state of the art, and identify the major players and the principal technological hurdles.[31] One of the agency's original program directors, for example, spent 6 months canvassing the energy community to identify white spaces in research on power system grids (Heidel and Gould, 2015). ARPA-E solicits additional thematic information by issuing requests for information (RFIs) on topics of interest, which include technical questions for which the answers can assist in assessing potential FOAs (ARPA-E, 2012).

One ARPA-E program director stated that program directors often draw on the knowledge base at DOE when formulating new projects, primarily through informal processes. They meet with DOE research managers and directors to learn what they are working on and solicit their comments on draft project ideas. Importantly, the program directors ask their DOE colleagues whether they are aware of other places where research related to a draft project theme is ongoing, and "you know you're on the right track if you get blank stares or they say 'that will never work'" (Heidel and Gould, 2015).

Once ARPA-E has identified technological white spaces, program directors convene technical workshops to consult leading experts from relevant scientific, engineering, and commercial communities, an exercise that informs the project development process and helps break down silos between disciplines. ARPA-E staff concurrently engage in discussions with other DOE personnel to identify gaps in existing research, determine the current state of the art, and draw on the department's internal expertise (ARPA-E, 2011b). The workshops serve as another means of determining the state of the art in a given field while providing a forum in which to discuss solutions to the critical challenges identified and determine performance targets

[31]Response by ARPA-E to question from Dr. Paul Broun, Chairman, U.S. Congress, House Subcommittee on Investigations and Oversight, Committee on Science, Space and Technology, Hearing, 112th Cong., 2d sess. (January 24, 2012), 73.

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the technical community thinks are aggressive yet reachable. While not all workshops lead to ARPA-E projects, they do inform the direction of projects in particular energy technology areas. At the close of each workshop, the program director may propose a new project, but must answer the questions shown in Box 2-1 satisfactorily before it can go forward.

BOX 2-1
Questions That Must Be Answered for New Projects

Project Technical Goals	• What is the global landscape of the field—science, technology, markets, players? • If successful, what specifically will the project accomplish technically? • Has the project been coordinated with DOE?
Mission Impact	• What impact would this project's success have on the agency mission should the technology become widely used: what is 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 them?
Transition	• What is the transition strategy (risk profile and time horizon)? • What are the nontechnical barriers to transition (policy, markets)? • Will the technology scale in cost and volume? • Who are the customers who will absorb this technology, and who will potential players be?
Project Metrics	• What are the metrics, milestones, and schedule for this project? • How much will the project cost and why?

SOURCE: ARPA-E, 2010a.

The proposed project is then subjected to "constructive confrontation" and debate with the participation of all ARPA-E program directors. On the basis of this dialogue, the program director proposing the project refines the proposal, incorporates feedback, and seeks approval from ARPA-E's director. If the director approves, a new project is created, and an FOA is released to the public, inviting proposals (Rohlfing, 2015).

Funding Opportunity Announcements

Throughout the federal research funding system, FOAs solicit research proposals through an open and transparent system. ARPA-E uses this system to request and receive research proposals, although it has implemented improvements to the system that have not been duplicated by other agencies. The FOA provides technical background and comprehensive information for potential applicants about the ARPA-E award process, performance expectations, funding limitations, and duration. ARPA-E FOAs fall into two broad categories:

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- **Focused—**These FOAs target specific areas of energy technology identified by ARPA-E as having a significant potential impact on one of its mission areas[32] (ARPA-E, 2014a). These FOAs require that program directors and other ARPA-E staff delineate clear and well-defined project goals.
- **OPEN—**These FOAs are solicitations of proposals for potentially disruptive technologies "across the complete spectrum of energy applications" and are intended to "ensure that the agency does not miss opportunities to support innovative energy R&D that falls outside of the topics of the various focused technology programs that develop after focused solicitations have closed (ARPA-E, 2015a). OPEN FOAs were released in 2009, 2012, and 2015. They account for about one-third of ARPA-E's funding support (Williams, 2015).

Both focused and OPEN FOAs feature a number of "technical categories" and "technical subcategories" of solicited themes for research, together with specific performance targets with respect to those themes. In a 2014 focused FOA for solar arrays, for example, "Category 1: System Solutions for High-DNI ["direct normal incidence," or high direct sunlight] Regions" comprised two subcategories with ARPA-E performance targets set as shown in Table 2-2. Submissions by applicants in response to FOAs must identify the technical subcategory or subcategories for proposed new technologies.

TABLE 2-2 Example of Focused Program Technical Targets from the MOSAIC Program Announced in 2014

Subcategory 1A: High-DNI System with Macro-Tracking

ID	Description	Target
1A.1	Solar energy harvesting efficiency	$\geq$ 30% at module output
1A.2	Production cost	< \$125/m^2
1A.3	Array height	< 2.5 cm
1A.4	Projected system degradation	< 1%/year

Subcategory 1B: High-DNI System with Embedded Micro-Tracking

ID	Description	Target
1B.1	Solar energy harvesting efficiency	$\geq$ 30% at module output
1B.2	Production cost	< \$150/m^2
1B.3	Array height	< 2.5 cm
1B.4	Projected system degradation	< 1%/year

SOURCE: ARPA-E, 2014b, p. 17.

[32]For example, a focused ARPA-E FOA released on December 8, 2014, invited proposals on the theme of micro-scaled optimized solar cell arrays with integrated concentration (MOSAIC). The technical target of this FOA is to foster a 50 percent improvement in solar-to-electrical power conversion over the performance of conventional "1-sun" flat plate photovoltaic modules (ARPA-E, 2015b).

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Application Process

Entities eligible for ARPA-E awards include universities, national laboratories, large and small private companies, nonprofits, "project teams," and consortia comprising such entities.[33] Foreign entities may apply for funding, but all work must be performed by subsidiaries or affiliates incorporated in the United States. Application for ARPA-E funding follows a three-step process.

Step 1. Concept Papers: Review Process

Applicants submit a five- to seven-page *concept paper*. External experts review an abstract of the proposal. This initial stage is intended to save applicants the time and cost of preparing applications with little likelihood of success. Concept papers were not widely used within DOE at the inception of ARPA-E. This step is widely viewed as a positive addition to the process and is critical in allowing ARPA-E program directors to shape projects. The reviewers assign each concept paper numerical scores according to two broad sets of criteria:

- **Impact of the proposed technology (50 percent)**—Reviewers consider (1) the extent to which the idea has potential for transformative and disruptive, rather than incremental, advancement over current technologies; (2) the extent to which the idea will positively impact at least one of the mission areas set forth by ARPA-E in the relevant FOA; and (3) the extent to which the applicant demonstrates awareness of competing commercial and emerging technologies and how the idea could result in significant improvements.
- **Overall scientific and technical merit (50 percent)**—Reviewers consider (1) the feasibility of the proposed work, (2) the extent to which the applicant proposes a "sound technical approach" superior to alternatives, (3) the extent to which outcomes and deliverables are clearly defined, (4) the extent to which the applicant identifies relevant techno-economic challenges, and (5) the demonstrated capabilities of the performers (ARPA-E, 2015a).

Following this review, the program director considers the evaluations and compiles a tentative list of concept papers to encourage to submit full applications based on a number of factors, including the numerical scores and comments received. Each FOA is accompanied by a Merit Review Plan, which is executed by an ARPA-E Merit Review Board. In carrying out the Merit Review Plan, a Merit Review Board, usually chaired by the program director who proposed the project and will oversee it, reviews and discusses the lists of papers with the program director, and the list is finalized through consensus. The Merit Review Board is not required to base its decisions solely on the numerical scores of the reviewers[34] (Orr, 2015). The ARPA-E director reviews the Board's recommendations and makes the final decision as to which applicants should be encouraged to submit a full application and which should be discouraged from doing so.

[33]42 U.S.C. § 16538(e)(3). "Project teams" refers to any entity with multiple collaborating players, including existing organizations and ad hoc teams.
[34]Under Secretary of Energy for Science and Energy Franklin Orr, noting that ARPA-E's selection decisions are not bound by the conclusions of the external reviewers, comments that "normal peer review kills many promising ideas" (Orr, 2015).

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Step 2. Full Applications: Selection Criteria and Process

Following review of concept papers, ARPA-E encourages some applicants to submit *full applications* providing information about prior, current, and pending sources of funding (both private and public) and an explanation of why other funding sources will not support the project. Full applications are reviewed by ARPA-E program directors and other personnel, including the director, along with leading external experts in the field. ARPA-E states that these comments are the most valuable component of the external review of an application. The reviewers must disclose any actual or apparent conflicts of interest. Reviewers include "world-class scientists, engineers, and leaders from the technical community" who convene in person for a review panel (DOE, 2010). Reviewers are asked to evaluate the applications and assign numerical scores, and provide comments according to four broad sets of criteria listed below, two of which—impact of the proposed technology and scientific/technical merit—are carried forward from the concept paper stage:

- **Impact of the proposed technology relative to the current state of the art (30 percent)**—Applicants are asked to demonstrate (1) the extent to which the idea is potentially transformative and disruptive (not incremental); (2) "profound understanding of the current state of the art" and an innovative approach to significantly improving it; (3) awareness of competing commercial and emerging technologies and how the idea would yield significant improvements over these technologies; and (4) a "reasonable and effective strategy" for transitioning the new technology from the laboratory to commercial deployment.
- **Overall scientific and technical merit (30 percent)**—Applicants must demonstrate (1) the extent to which the idea is "unique and innovative"; (2) clearly defined outcomes and deliverables; (3) the feasibility of the proposed work based on preliminary data, background information, and/or sound scientific and engineering practices and principles; (4) a sound technical approach, including "appropriately defined technical tasks"; and (5) identification of major technical R&D risks and feasible, effective risk mitigation strategies.
- **Qualifications, experience, and capability (30 percent)**—Applicants must demonstrate (1) the skill and expertise necessary to execute their project plan, based on prior experience with R&D of similar risk and complexity; and (2) access to the equipment and facilities necessary to execute the plan.
- **Management plan (10 percent)**—Applicants must demonstrate (1) a plausible plan for managing people and resources; (2) allocation of appropriate levels of effort and resources to tasks; (3) a reasonable project schedule, including major milestones; and (4) the appropriateness of the budget relative to the task (ARPA-E, 2015a).

Once external evaluations have been completed, the Merit Review Board, usually chaired by the program director who initiated the relevant FOA, reviews the evaluations, generates "discuss" lists, and meets in person with the review panel to discuss applications. Applicants are allowed to read reviewers' comments and submit rebuttal comments before the Merit Review Board makes funding recommendations. The Merit Review Board then considers the evaluations, any rebuttal comments from applicants, and the technical merit review criteria and program policy considerations, and makes its recommendation to the ARPA-E "selection

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official" (the ARPA-E director). The selection official decides which full applications will be selected to negotiate terms of an award. Again, there is no obligation to use the scoring by the reviewers as the sole factor in determining which projects are selected, or to rank applications according their reviewer scores.

In a 2012 audit, ARPA-E program directors told the Government Accountability Office (GAO) that, in addition to the above four criteria, they were allowed to consider other factors, one of which was funding of a broad range of potentially transformational technological innovations with varying levels of risk to address a given technological challenge. This approach was seen as increasing "the likelihood that at least one of them would work." The program directors also indicted that during the selection phase, they sometimes negotiated with applicants to adjust the proposed budget, the project scope and timeframe, and milestones to be achieved (GAO, 2012). This approach also demonstrates how ARPA-E presently manages the inherent trade-off between "bias" and "information" during the selection process and how it tries to aggregate information from its reviewer cohorts to maximize value during project selection (Boudreau et al., 2016; Hoffman et al., 2015; Li and Agha, 2015).

Step 3. Reply to Reviewer Comments

Applicants are given an opportunity to *reply to reviewer comments* (DOE, 2010). In contrast to DARPA, which does not share reviews with applicants, ARPA-E sends reviews to applicants prior to a final determination and provides the opportunity to prepare a reply to reviewer comments. Typically the agency limits the length of replies, often to four pages or less (Rohlfing, 2015).

Project Selection and Implementation

ARPA-E supports two categories of projects:

- **Proof-of-concept**—These projects are intended to provide the first preliminary data to prove or disprove new technology concepts. They are limited in cost (under $1 million) and duration (6–18 months).
- **Technology development**—These projects are intended to develop technology from ideas to laboratory-scale prototypes operating at agreed-upon specifications. Their duration is typically 36 months and their cost $2–10 million.

Both are solicited, selected, and implemented following the same process just described.

Most of ARPA-E's projects are based on focused, thesis-driven programs centered on a theory of change. However, the agency's initial personnel decided that focused programs should be augmented by the occasional open solicitations discussed earlier, intended to cast a broad net and encourage novel and creative ideas that staff had not yet conceived of and that had the potential to inspire whole new programs (Danielson, 2015).

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Project Management

Negotiations with Selected Applicants

After ARPA-E selects applicants for an award, the agency engages in negotiations with the potential recipients for a final award. This process is expected to take about 90 days. Program directors work with recipients to establish a work plan with technological milestones that include specific go/no go decision points over the course of the project. ARPA-E reviews awardees' budget documents, and may require additional information and documentation. The parties must reach agreement on how patents and other intellectual property rights will be handled; potential conflicts of interest identified by awardees are reviewed; and ARPA-E evaluates the project's environmental impact.

Most ARPA-E awards are made using cooperative agreements between the agency and successful applicants. The agency also has statutory authority to provide awards in the form of cash prizes, grants, contracts, and "other transactions."[35] In cooperative agreements, "substantial involvement is expected between the executive agency and the…recipient when carrying out the activity contemplated in the agreement."[36] Cooperative agreements serve as the legal foundation for ARPA-E's active and continuous engagement in a project, and provide that

- ARPA-E may intervene in the project at any time;
- ARPA-E's role is not limited to administration of the award but includes substantial involvement in the direction and redirection of the technical aspects of the project as a whole; and
- ARPA-E may terminate or redirect projects that fail to achieve predetermined go/no go decision points or technical milestones/deliverables.[37]

Cost Sharing

Prime recipients of an award are required to provide at least 20 percent of the total project cost.[38] The prime recipient's share may consist of cash or in-kind contributions from the prime recipient or subrecipients[39] (ARPA-E, 2015a). Large businesses are "strongly encouraged" to provide more than 20 percent of the total project cost; conversely, ARPA-E has reduced minimum cost-share requirements for small businesses (10 percent with a 1-year grace period) and nonprofits and universities (5 percent) (ARPA-E, 2015a). Under the America COMPETES Act, program directors are responsible for "identifying innovative cost-sharing arrangements for ARPA-E projects."[40] However, the agency's awards remain governed by general federal cost-sharing rules and requirements, which limit innovative arrangements (ARPA-E, 2015a).

[35]42 U.S.C. § 16538(f).
[36]31 U.S.C. § 6305.
[37]ARPA-E Model Cooperative Agreement, Special Terms and Conditions, Clause 7.a.
[38]42 USC §16352 (2017).
[39]In-kind contributions may include personnel costs; facilities; administrative costs; indirect costs; the rental value of buildings and equipment; and the value of a service, other resource, or third-party in-kind contribution. 2 CFR 910.130 (2017)
[40]42 U.S.C. § 16538(g)(2)(B)(v) (2017).

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Project Milestones

ARPA-E works with awardees to develop acceptable project milestones by starting from the hoped-for deliverable and working backward along the development path to establish critical binary go/no go milestones, typically beginning early in the second year of the project. Awardees tend to propose milestones they believe they can achieve, whereas the agency encourages them to be aggressive and push the milestones "to the edge, but not over." Milestones are expected to be specific, unambiguous, and quantifiable. They may be revisited and renegotiated "if there is still a clear path to the final objective" (Rohlfing, 2015). As a result of go/no go reviews, the terms of cooperative agreements provide that ARPA-E may

- authorize continuation of the project,
- redirect the project's work,
- place the project on hold pending further supporting data,
- suspend or terminate the project per the agreement, or
- take "other appropriate actions" (ARPA-E, n.d., p. 6).

Technology-to-Market (T2M)

Before receiving award funds, awardees are required to develop a T2M plan in close coordination with ARPA-E's T2M advisors. Commercialization strategies developed to meet this requirement include training and the development of the business information necessary to understand market needs and tailor technology development to address those needs. ARPA-E also helps awardees develop relationships with relevant government agencies, technology transfer offices, companies, investors, and other organizations to facilitate transition to the commercial phase (ARPA-E, 2016).

Project Funding

Project funding is set aside in its entirety at the beginning of a project to guarantee availability of the funds required to continue funding projects that are successfully meeting their milestones regardless of future appropriation levels.[41] The average award size is $2.7 million. Award recipients invoice ARPA-E periodically for costs incurred. Prior to payment, the agency must determine that each invoiced cost is "reasonable, allowable and allocable."[42] ARPA-E's goal is to pay invoices within 30 days.

One important point of differentiation from other DOE offices has to do with funding. ARPA-E's goal for successful projects is for them to attract funding from other sources to continue the work and carry the technology farther along the development path. If the idea shows merit during its time as an ARPA-E project, the agency may try to extend additional funding

[41]"One of the great things about ARPA-E and the way we're structured is that we fully fund our projects right up front. So when we say we've awarded $900,000 to a specific project, that money is already set aside from our current year's budget. So even if that project takes 2–3 years to complete, those scientists don't have to worry about their budget being cut mid-project. That makes a huge difference. Our researchers can stay focused on the project at hand and hopefully knock down these technical challenges to get these technologies moving and change our energy future." Personal consultation with ARPA-E Deputy Director Cheryl Martin, *The Energy Collective* (August 8, 2013).

[42]2 C.F.R. 200, *Uniform Administrative Requirements, Cost Principles and Audit Requirements for Federal Awards.*

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while the project team seeks funding from other sources, but ultimately, other funders must step in to sustain the work. By contrast, other DOE offices often have technology roadmaps and seek to sustain particular technologies much farther through the stages of development.

Monitoring and Continuous Engagement

ARPA-E remains closely engaged with awardees from the inception of a project through its conclusion. An initial program kickoff meeting is held to convene all of the performers from a given focused technology program, provide thumbnail overviews of all of the projects in the program, and begin providing awardees with information on such subjects as technical challenges and scientific ideas by means of tutorials and invited talks. Program directors subsequently engage in "active project management," which includes review of quarterly performer reports, regular site visits, meetings, conference calls, and written feedback on results and reported quarterly progress. The subjects of these contacts can include general reviews of progress relative to milestones, specific responses to a new challenge, and identification of anticipated problems and potential solutions. Site visits enable visual confirmation of progress toward milestones and frank exchanges about nonperformance. During each subsequent year of a focused technology program, ARPA-E holds an annual meeting convening all performers of projects within the program, who provide updates on progress and discoveries to the entire group of performers.

When ARPA-E finds that a project is not meeting its milestones, it acts to address the situation. The first line of defense is the frequent contact between the ARPA-E program director and her or his staff and the performer team, which helps avoid either party being surprised to learn of the difficulty meeting milestones. In more challenging cases, contact by telephone or meetings may increase to weekly frequency. Actions taken include complete termination of the project, limited extensions of time to allow projects to meet a given milestone, and revision of milestones and objectives. ARPA-E indicated that as of May 2015, the agency had terminated a total of 21 projects prior to the end of their cooperative agreements' end dates because of failure to achieve stipulated milestones (Williams, 2015).

ARPA-E Energy Innovation Summit

ARPA-E hosts annual Energy Innovation Summits to convene national leaders in energy from industry, academia, and government. The agency requires that all performers with active awards attend, and provides each a booth to showcase their research. One major goal of the summit is to connect project performer teams with potential sources of future support for their research and eventual technology development. Thus, ARPA-E also works to ensure that potential private and public follow-on funding sources—such as venture firms, banks, established technology development firms, other offices of DOE, and other federal funding sources—attend in addition to the performers. A summit typically draws about 2,000 attendees (Reitenbach, 2015). The summits "have become major technology showcase events in Washington, attracting large attendance and featuring prominent business, executive branch and bipartisan Congressional leaders in speaking roles" (Bonvillian and van Atta, 2011). Dr. Cheryl Martin, former deputy director for commercialization at ARPA-E, offered a perspective on the 2015 summit in an interview:

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> …When ARPA-E started not even six years ago…it was a startup agency, and the first summit was formed to basically talk about what the agency could be and to show that it was supported very uniformly, you know, across Congress and business and academics, but the first conference night we didn't have any projects. We had potential. And as we've evolved as an agency, we have $1.1 billion, 400 projects that we've funded, and down on the floor today, we have 250 booths of technologies where, some of them are actually real products now. And so you see that movement from idea and growth and new certainly not…maturity, but it's an evolution that's real, and I think that the buzz at the summit now reflects that. (E&ETV, 2015)

The summits feature a "technology showcase" where breakthrough energy developments from ARPA-E performers are featured. The showcase also features other promising innovations in the energy field, regardless of whether they have been supported by ARPA-E,[43] highlighting applicants that did not receive awards but that, in the agency's view, deserve attention in the energy research community.

Summary of ARPA-E Programs

As of October 2016, ARPA-E had invested over $1 billion in more than 500 projects. It had launched 38 focused programs and conducted three open funding solicitations (in 2009, 2012, and 2015). Table 2-3 provides the names of all these programs, along with the number of projects receiving funding under each and the total amount of funding made available for each.

TABLE 2-3 ARPA-E Programs as of October 2016

Program Name	Number of Projects	Authorized Funding Amount ($ Million)
OPEN 2009	41	175.0
Batteries for Electrical Energy Storage in Transportation (BEEST)	10	32.4
Innovative Materials and Processes for Advanced Carbon Capture Technologies (IMPACCT)	15	41.0
Electrofuels	13	48.7
Agile Delivery of Electrical Power Technology (ADEPT)	14	38.7
Building Energy Efficiency Through Innovative Thermodevices (BEETIT)	17	37.6
Grid-Scale Rampable Intermittent Dispatchable Storage (GRIDS)	12	34.0
Plants Engineered to Replace Oil (PETRO)	10	55.4
High Energy Advanced Thermal Storage (HEATS)	15	37.9
Rare Earth Alternatives in Critical Technologies (REACT)	14	37.5
Green Electricity Network Integration (GENI)	15	42.3
Solar Agile Delivery of Electrical Power Technology (Solar ADEPT)	7	13.5
Methane Opportunities for Vehicular Energy (MOVE)	14	40.5

[43]Statement of ARPA-E Director Arun Majumdar, U.S. Congress, House Subcommittee on Energy and Water Development and Related Agencies, Appropriations Committee, Budget Hearing, March 28, 2012.

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Program Name	Number of Projects	Authorized Funding Amount ($ Million)
Advanced Management and Protection of Energy Storage Devices (AMPED)	14	30.3
Small Business Innovation Research/Small Business Technology Transfer (SBIR/STTR)	6	12.8
OPEN 2012	67	158.7
Innovative Development in Energy-related Applied Science (IDEAS)	6	2.5
Robust Affordable Next Generation Energy Storage Systems (RANGE)	22	36.2
Reducing Emissions using Methanotrophic Organisms for Transportation Energy (REMOTE)	15	35.8
Modern Electro/Thermochemical Advancements for Light-metal Systems (METALS)	18	35.9
Full-Spectrum Optimized Conversion and Utilization of Sunlight (FOCUS)	13	35.3
Strategies for Wide Bandgap, Inexpensive Transistors for Controlling High Efficiency Systems (SWITCHES) & SBIR/STTR	14	29.0
Reliable Electricity Based on Electrochemical Systems (REBELS)	13	33.7
Delivering Efficient Local Thermal Amenities (DELTA)	11	30.0
Methane Observation Networks with Innovative Technology to Obtain Reductions (MONITOR)	11	30.0
Accelerating Low-cost Plasma Heating and Assembly (ALPHA)	9	30.0
Cycling Hardware to Analyze and Ready Grid-Scale Electricity Storage (CHARGES)	2	—
Advanced Research In Dry cooling (ARID)	14	30.0
Transportation Energy Resources from Renewable Agriculture (TERRA)	6	30.0
Generators for Small Electrical and Thermal Systems (GENSETS)	14	55.0
Traveler Response Architecture using Novel Signaling for Network Efficiency in Transportation (TRANSNET)	5	14.5
Micro-scale Optimized Solar-cell Arrays with Integrated Concentration (MOSAIC)	11	24.0
OPEN 2015	38	125.0
Network Optimized Distributed Energy Systems (NODES)	8	33.0
Generating Realistic Information for the Development of Distribution and Transmission Algorithms (GRID DATA)	5	11.0
Single-Pane Highly Insulating Efficient Lucid Designs (SHIELD)	0	31.0
Integration and Optimization of Novel Ion-Conducting Solids (IONICS)	16	37.0
ENergy-efficient Light-wave Integrated Technology Enabling Networks that Enhance Datacenters (ENLITENED)	0	25.0
Renewable Energy to Fuels through Utilization of Energy-dense Liquids (REFUEL)	0	30.0
NEXT-Generation Energy Technologies for Connected and Automated on-Road vehicles (NEXTCAR)	0	30.0
Rhizosphere Observations Optimizing Terrestrial Sequestration (ROOTS)	0	30.0

NOTE: Funding amount for the CHARGES program redacted due to the small number of awardees.
SOURCE: DOE, 2015.

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3

ARPA-E's Internal Operations: Culture, People, and Processes

In accordance with its statement of task (Box 1-1 in Chapter 1), the committee undertook an operational assessment to "appraise the appropriateness and effectiveness of the agency's structure to position it to achieve its mission and goals." This chapter describes and assesses ARPA-E's internal operations, addressing the following specific charges in the statement of task:

- Evaluate ARPA-E's methods and procedures to develop and evaluate its portfolio of activities;
- Examine appropriateness and effectiveness of ARPA-E programs to provide awardees with non-technical assistance such as practical financial, business, and marketing skills;
- Assess ARPA-E's recruiting and hiring procedures to attract and retain qualified key personnel;
- Examine the process, deliverables, and metrics used to assess the short and long term success of ARPA-E programs;
- Assess ARPA-E's coordination with other Federal agencies and alignment with long-term DOE objectives;
- Provide guidance for strengthening the agency's structure, operations, and procedures;
- Evaluate, to the extent possible and appropriate, ARPA-E's success at implementing successful practices and ideas utilized by the Defense Advanced Research Projects Agency (DARPA), including innovative contracting practices; and
- Reflect, as appropriate, on the role of ARPA-E, DOE, and others in facilitating the culture necessary for ARPA-E to achieve its mission.

DEFINING ORGANIZATIONAL FEATURES OF ARPA-E

Through the course of its deliberations and analyses of the evidence gathered for this assessment, the committee found that ARPA-E benefits from three defining organizational features:

- The director exercises technical and leadership skills that enable a culture of empowerment to be sustained.

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- ARPA-E's program directors are empowered with the authority, responsibility, and ability to make program- and project-related decisions.
- Active project management is important to ARPA-E.

Collectively, these three features have the potential to contribute to ARPA-E's ability to achieve its intended mission and goals. The absence of these features would not guarantee failure, and their presence does not ensure success. However, these features are important to creating conditions that can enable success. ARPA-E's culture of openness and empowerment encourages risk taking. ARPA-E's program directors have wide autonomy to develop new focused technology programs and manage projects within those programs. The agency selects projects to fund through a multifaceted process that entails evaluating each project's potential, if successful, to help achieve the agency's goals instead of adhering strictly to ranking of external peer reviewer scores.

This chapter presents the evidence supporting the importance of these organizational features, together with the committee's findings and recommendations on ARPA-E's internal operations.

METHODS

The committee developed a framework for evaluation based upon the individual charges mandated in the statement of task. As described in detail in Appendix B, the committee used both qualitative and quantitative methods to address the implicit research and evaluative questions associated with each of these charges. Qualitative methods included reviewing archival ARPA-E planning documents (e.g., strategic planning documents and annual reports), as well as solicitations, application and selection processes, and per-project milestones; consulting with present and former employees of ARPA-E and other U.S. Department of Energy (DOE) offices and programs, performers,[1] and other experts; and attending agency program meetings and the annual Energy Innovation Summit to identify and observe key stakeholder interactions. Quantitative methods included examination of descriptive statistics and regression analysis of data related to the program directors' roles, responsibilities, and activities.

From this rich collection of data, a picture emerged of the three defining organizational features listed above. The remainder of this chapter explores these features in detail. The chapter ends with a summary of the committee's findings and its recommendations with respect to ARPA-E's internal operations.

ARPA-E'S CULTURE, PEOPLE, AND PROCESSES: A QUALITATIVE AND QUANTITATIVE ANALYSIS

ARPA-E exhibits a number of features that suggest the organization's policies and practices, internal structure, and culture are interlinked and interdependent in a way that are essential for strategic management of innovation (Kfir, 2000). Organizational culture has been found to have a particularly important role in supporting technology innovation since it unites the aims of

[1]"Performers" is the term used to denote ARPA-E awardees.

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individuals in the organization to achieve excellence by encouraging repeatability of behaviors, actions, and attitudes for both individuals and groups (Berry et al., 2006; Hurley and Hult, 1998; Koźmiński and Obłój, 1989; Lyons et al., 2007; Szczepańska-Woszczyna, 2014; Tellis et al., 2009). Culture is also important for enabling public agencies to recruit and retain talented personnel to execute on agency mission and maintain institutional memory (Goodsell, 2011). Much as at the Defense Advanced Research Projects Agency (DARPA), ARPA-E seeks to maintain a culture that encourages key staff to commit to advancing its mission while generating the admiration and respect of those outside of the agency—essentially the "mission mystique" (Goodsell, 2011).

Culture is interdependent with people and processes. The latter are where a cultural orientation toward innovation become operationalized to help an organization achieve its objectives (Bina, 2012; Gonzalez-Padron et al., 2008; Szczepańska-Woszczyna, 2015, p. 397). In the innovation context, this refers to an organization's willingness to chart new territory and orient toward future and external events while thinking beyond what technology the market currently demands to envision what will be useful and in demand—or even transformational—if developed (Christensen and Bower, 1996; Narver and Slater, 1990; Tellis et al., 2009; Yadav et al., 2007).

When it comes to people, empowering individuals allows innovation-oriented organizations to recruit and retain top talent. Such empowerment is a critical element of seeking new directions and fostering innovation rather than being incentivized only to seek short-term commercial rewards (Aghion et al., 2010; Kfir, 2000; Nijstad et al., 2012; Szczepańska-Woszczyna, 2015).

The findings reported here were drawn from a quantitative analysis focused on ARPA-E's discretion to select projects for funding through a process that relies on program director discernment and discretion rather than strict adherence to a particular bureaucratic process; to fund projects that may appear riskier than others but are deemed to hold greater potential for impact if successful; and to engage actively in ongoing projects by altering project milestones, budgets, and timelines when necessary. This quantitative analysis was supplemented by a qualitative analysis drawn from discussions with the founding ARPA-E director; current and former program directors; leaders of other DOE offices and programs, including those at the national laboratories; presentations at the study committee's meetings by ARPA-E leadership, DARPA leadership, and other outside experts[2]; and case studies prepared by the committee (Appendix C). Appendix B briefly describes the methods used in developing this analysis. Full details are found in the consultants' reports (Appendix F).

ARPA-E's Culture of Innovation and Risk Taking

Research points to four critical organizational elements related to culture that promote innovation: (1) exceptional tolerance for failure, (2) the ability to deal with uncertainty and risk, (3) strong communication channels, and (4) nurturing leadership (Amabile et al., 1996; Holmstom, 1989; Hurley and Hult, 1998; Jaworski and Kohli, 1993; Kanter, 1983; Lyons et al., 2007; Nelson, 1962; Rosenberg, 1996; Szczepańska-Woszczyna, 2015; Utterback, 1974). A number of ARPA-E's activities and procedures indicate the agency features 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. This tolerance

[2]Agendas from committee meetings providing the names and affiliations of presenters are included in Appendix E.

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of failure of is an important characteristic of organizations or researchers seeking to produce innovative outcomes since learning what does not work at the level desired can be quite valuable and often provides guidance for ultimately developing a successful technology. A friend of Thomas Edison, for example, once learned that the inventor and his team had conducted more than 9,000 experiments in an attempt to develop nickel-iron batteries to no avail, and opined as to what a shame it was to have wasted the effort. Edison famously retorted that the effort was not wasted but had produced many results and revealed "several thousand things that won't work" (Dyer and Martin, 1910, p. 616). This means, however, that outcome metrics for innovation are inherently noisy, and decision making around innovation must be less sensitive to performance (Holstrom, 1989). Hence much focus on metrics has gone to more easily observable ones such as organizational attributes, specific actions that are known to support and encourage innovation, and intermediate outputs.

A critically important difference between ARPA-E and other DOE offices is its statutory mandate to identify and promote ideas with the promise of being revolutionary, and to support ones that industry is unlikely to support alone. In other words, ARPA-E was created to tolerate risk and foster activities that would lead to transformative technology innovations and to do so by being structured and operating in ways that are innovative for a DOE program. Two styles of managing research for innovation have been described in the literature. One is exploitation, where the research is aimed at producing incremental improvements along a known technology development curve. Exploration, on the other hand, seeks to discover entirely new technology development curves. Exploitation often entails the use of known research tools and activities, while exploration involves potentially wasted effort, inferior actions, and many early failures. Some researchers suggest that nurturing these two different types of innovation requires different management practices. On the one hand, exploitation can be incentivized effectively with standard short-term, pay-for-performance contracts and strict termination rules for failure. On the other hand, motivating exploration requires tolerance for failure and long time horizons (Manso, 2011).

At first glance, ARPA-E may appear to fall squarely within the exploration parameters that Manso describes. On closer inspection, though, some ARPA-E activities could be characterized as attempting to exploit as yet uncaptured value along known technology development curves. As seen in Figure 3-9 later in this chapter, ARPA-E projects, by design from the agency's mandate, can be seen as sitting mostly in "Pasteur's quadrant," at the intersection of basic and applied research (Stokes, 1997). Such organizations are sometimes called "ambidextrous" since, in an innovation context, they are trying both to explore and exploit (Tushman et al., 2010). ARPA-E is organized to include "an interrelated set of competencies, cultures, incentives and senior team roles," suggesting that it can simultaneously and cost-effectively promote exploration and exploitation, and thus should be better positioned to support innovation compared with organizations with singular organizational designs (Tushman et al., 2010). ARPA-E's differentiation among its programs and projects suggests that the agency may be positioned to exploit this ambidextrous advantage, although evidence of the agency's long-term performance will be seen only over time.

Given ARPA-E's mandate to seek out and support risky but potentially valuable technology, the agency must be able to deal with risk and uncertainty. One recognized way to mitigate the risk of uncertainty is to focus research on learning rather than achievement of results (Nelson, 1962). Rosenberg (1996) argues that innovation is an inherently uncertain task, making it impossible to know the probability distribution of outcomes. Thus, for ARPA-E to be well

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positioned to support innovation, it must maintain an appetite for risk and uncertainty (Amabile et al., 1996; Hurley and Hult, 1998; Jaworski and Kohli, 1993; Kanter, 1983). This observation is intuitive since by "definition, innovation is a novelty-producing process, consisting of a string of non-routine decisions made under uncertainty" (Lyons et al., 2007, p. 182). The organization must also have its own capacity for change and internal innovation. An open culture receptive to new ideas, willing to experiment with procedures and programs to improve them, allows a public agency to be a dynamic partner in innovation (Goodsell, 2011).

The evidence presented later supports the notion that ARPA-E's director and program directors seek to develop focused programs based on new ideas and risk, supporting those ideas they believe have enough potential to warrant investment. Both qualitative and quantitative evidence points to cultural norms and values at the agency that attract such risk-oriented individuals and encourage them to seek out truly new ideas and pursue those with the potential to be transformative. Such a cultural norm of empowering staff is a critical element of fostering innovation (Kfir, 2000; Nijstad et al., 2012; Szczepańska-Woszczyna, 2015). This means an ability to avoid the incrementalism often found in government programs that fund research.[3] Ideas funded by ARPA-E need not fit neatly into one specific category, but this does not mean the ideas are passed from office to office.[4]

A key challenge for any organization is to promote innovation without producing uniformity of ideas (Lyons et al., 2007). One such norm that can help support the search for new ideas is to encourage constructive intellectual debate on ideas (Lyons et al., 2007). Nearly all of the individuals consulted during this study mentioned this norm and its importance for ARPA-E, pointing to the agency's early adoption (and adaptation) of the well-known core norm of "constructive confrontation" made famous by Intel CEO Andy Grove (Staley, 2016). At ARPA-E, constructive confrontation entails two key features. First, individuals can debate the technical merits of ideas without fear of reprisal and with confidence that any criticism offered will be taken as constructive, with the intent of strengthening the ideas, rather than as a personal attack. Second, the committee repeatedly heard that the program directors and other staff have genuine camaraderie with each other. They have a professional rapport and trust that they are working together for the common goal of achieving the agency's mission and goals. This gives ARPA-E staff—and especially program directors—the confidence to take risks, pursue ideas with the potential to create something new, and freely communicate with anyone in the agency (Berry et al, 2006).

Individuals consulted for this study reported that ARPA-E demonstrates strong communication channels across the agency at both the structural and cultural levels. Program directors all demand rigorous critiques of their pitches for new focused technology projects. Several former program directors expressed the sentiment that the worst thing that can happen when an idea is first pitched is for no one to challenge it. Program directors also expect that the agency director will engage with them, providing critique and feedback regarding programs and projects, and do so constructively and in a way that program directors do not fear personal attack or reprisal. These strong communication channels constitute an important tool for dealing with uncertainty in research and development (R&D), being both a source of idea production and a means for problem solving (Utterback, 1974). While planned coordination is insufficient for the transfer of knowledge within an organization, open lines of communication are necessary in

[3]Interview with Le Minh.
[4]Interview with Ravi Prasher.

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settings where outcomes are uncertain. An organization's structure can either augment or impede internal communication as well (Utterback, 1974). The importance of this culture is seen at ARPA-E's "Program Director Week," a once-a-month event when all program directors are required to be in the office to build camaraderie, embrace constructive confrontation, and share lessons learned in developing and managing programs.

ARPA-E's mandated focus on innovation means the agency needs to be orientated to the future. Maintaining a future orientation means evolving and adapting processes intended to identify potentially groundbreaking ideas and technologies. ARPA-E has described its processes as the search for "white space." Searching for white space for ARPA-E entails pursuing two distinct but related areas of research with the objective of producing energy technology innovations: the first is the pursuit of technological ideas or approaches that are truly novel or greatly underexplored; the second is a deliberate attempt to fill gaps left in other research or funding programs. In addition to this search, future orientation means keeping an influx of talented program directors empowered to seek white space, construct new programs, and actively guide their projects. Building and maintaining a future-oriented culture in turn requires the creation of new learning curves for the pursuit of white spaces, as well as expertise, enthusiasm, and initiative across the agency.

People Who Support ARPA-E's Culture of Innovation and Risk Taking

Intellectually, it is difficult to separate the impact and role of people from culture and processes, a difficulty reflected by the evidence gathered for this study. People build and maintain an organization's culture, and agency culture was an oft-cited reason for wanting to work at ARPA-E. Nonetheless, it is useful to consider here the roles played by key agency personnel. This section presents qualitative data and quantitative data with descriptive and analytical statistics for key attributes of program directors to enable a better understanding of their characteristics and active management practices. To conduct these analyses, the committee worked with external consultants who examined anonymized data detailing the specific performance of individual projects against award milestones. Those data were provided by ARPA-E and anonymized and aggregated to protect sensitive information.[5]

The body of research on managing R&D for innovation strongly suggests that ARPA-E can help ensure a culture supportive of innovation and risk taking by attracting and hiring (1) a visionary and technically expert director who creates an environment that demands new ideas, change, and risk and hence tolerance for failure; and (2) empowered program directors who want to work in such an environment. The committee evaluated the data gathered by its consultants. While the dataset is of high quality, it must be understood in context. As mentioned several times in this report, ARPA-E is a relatively young agency, and so the available time series is short and catalogs only its initial years, in this case the first 6 years of agency operation. While such a short time series does not allow for drawing conclusions as robust as policy makers may want, the data still clearly suggest that ARPA-E has done well in this regard.

[5]The working paper developed by Goldstein and Kearney (2016) includes a more detailed description of the data collected, the methods used, and the authors' analysis and conclusions. The authors can be reached via email at anna_goldstein@hks.harvard.edu or mkearney@mit.edu.

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Leadership and Vision of the ARPA-E Director: Qualitative Analysis

As noted above, the committee identified the director's key role in ARPA-E as a defining organizational feature of the agency. The director bears significant responsibility for ensuring that program directors are empowered and for fostering and sustaining a culture that promotes innovation. The director also holds high responsibility for preserving and updating the values of the agency's mission—putting them into practice (Terry, 2003). The importance of this responsibility was reinforced through the committee's discussions with former ARPA-E directors, program directors, and others who interacted with the program while at DOE.

ARPA-E's director is expected to establish and nurture an organizational culture that increase the agency's capacity to promote innovation. A principal challenge is managing "the inherent paradox between a strong culture and innovation" (Lyons et al., 2007, p. 182). Key ways to do this include (1) serving as a role model by focusing on the agency's interests rather than personal gain; (2) articulating an inspiring, energizing vision; (3) fostering intellectual stimulation by encouraging challenges to the status quo; (4) providing individualized consideration and support for team members; and (5) ensuring that the organization designs and implements structures, systems, and processes that reflect and establish an innovation-oriented culture (Bass, 1985; Hurley and Hult, 1998; Lyons et al., 2007; Nijstad et al., 2012, p. 312; Szczepańska-Woszczyna, 2015). These structures, systems, and processes are important in attracting talented personnel who can achieve an organization's mission and goals (Szczepańska-Woszczyna, 2015).

Discussions with personnel from ARPA-E and DOE suggest that ARPA-E personnel already have an intuitive grasp of the importance of leadership, especially transformational leadership, in fostering the agency's capacity to carry out its mission. The consulted individuals emphasized the importance of leadership to performance, to attracting talent, and to enabling the agency to pursue ideas with the potential to be radically innovative. They also emphasized that it is critical for leaders to create a climate where specific aspects of a culture of innovation can flourish and operate—including an appetite for new ideas, change, and risk; tolerance for failure; empowerment of individuals; and an orientation to the future. ARPA-E directors also engage externally to accomplish the program's mission, with their role thereby extending to working with Congress and creating partnerships with other energy research programs, in addition to the role of serving as an exemplar and leader to ARPA-E staff.

Individuals also stated their belief that the ARPA-E director must be able to foster and maintain the trust of agency staff, especially the program directors, and of national leaders. The director must be widely recognized and respected as an accomplished scientist or engineer. This requirement was anticipated by ARPA-E's authorizing legislation, which stipulates that the agency's director is to be an individual who, "by reason of professional background and experience," is "especially qualified" to advise the secretary of energy on "matters pertaining to long-term and high-risk barriers to the development of energy technologies."[6]

[6]42 U.S.C. § 16538(d)(2).

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Acknowledged technical competency and skill serve as a foundation for building trust that in turn enables empowerment and autonomy among program directors and other key personnel. Program directors must be able to trust that the director will engage with them regarding the technical details of proposed programs, as well as evaluation of which projects merit funding. While only the director is authorized to make funding decisions, program directors are the domain experts who serve as the heart of the merit review and decision-making processes. They want the director to be fully engaged and constructively supportive throughout those processes. Program directors consulted for this study said further that they wanted to know the director will trust them when they make recommendations to fund, redirect, and terminate projects.

Program Director Characteristics: Quantitative Analysis

Program directors arguably serve the most critical function at ARPA-E. They are chiefly responsible for serving as opportunity creators and idea harvesters, carrying out the vital efforts necessary to identify and support those researchers who are developing potentially disruptive ideas within an emerging technology field and have the ability to perform the research (Bonvillian and van Atta, 2011). Biographical research on ARPA-E program directors demonstrates that they all hold research doctorate degrees in science or engineering fields and are diverse in terms of career stage and professional background, but not gender. Program directors are overwhelmingly male.

For this analysis, the committee collected data on 32 program directors (29 males and 3 females). Using a career stage taxonomy, the committee found that the year in which program directors received their undergraduate degree ranged from 1971 to 2007. Taking date of undergraduate degree as a reasonable proxy for career stage, three categories were created: late career (undergraduate degree pre-1985), midcareer (undergraduate degree 1985–2000, inclusive), and early career (undergraduate degree post-2000). The data show that late-career program directors managed 43 percent of projects selected for funding, midcareer program directors 41 percent, and early-career program directors 16 percent. Using a professional background taxonomy, the prior careers of program directors who had held only academic jobs following attainment of their final degree were categorized as Academia, those with careers only in industry as Industry, and those that had held positions in both academic and industry settings as Blended. The Academia program directors accounted for 28 percent of the total, Industry program directors accounted for 34 percent, and Blended program directors for 38 percent. Of the 16 program directors who have departed ARPA-E, 2 have since had blended career paths, in this case meaning they have held positions in a combination of Academia, Industry, or Government since departing ARPA-E, 7 hold Academia positions, 2 still hold a position elsewhere in the federal government, and 5 are in Industry positions. These data are shown in Figure 3-1.

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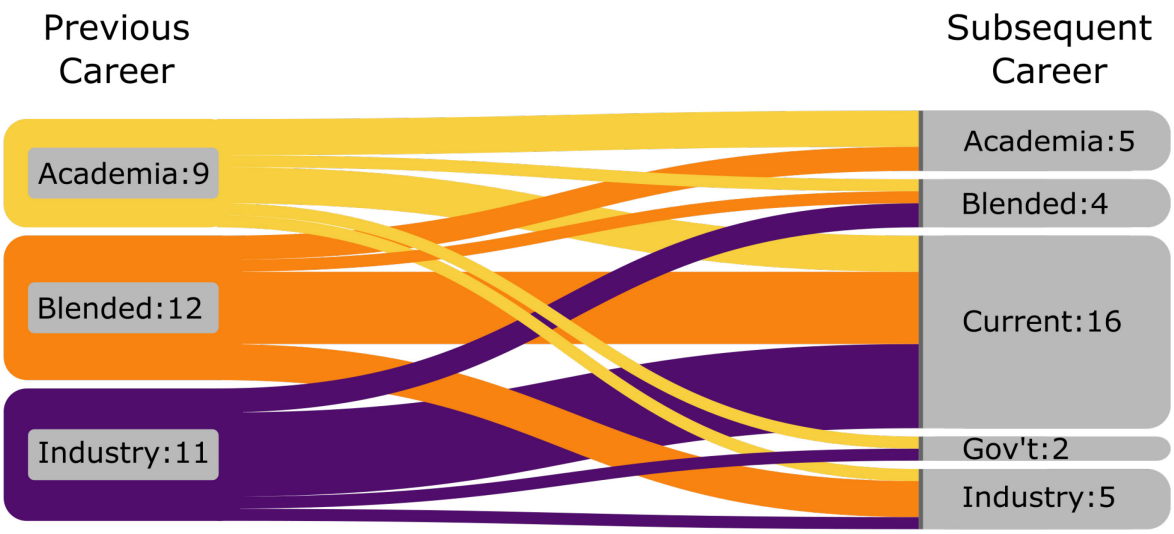

FIGURE 3-1 Careers pathways of ARPA-E program directors as of May 2017.
NOTES: This Sankey diagram presents the program directors' careers before and after ARPA-E. For example, 11 program directors came from industry. N = 32.

Recruiting Program Directors

ARPA-E's primary method of recruiting program directors is by word of mouth. Current and alumni program directors suggest individuals that ARPA-E may wish to consider, and they inform their professional networks of whether they think ARPA-E is a valuable place to work. While this process could not be observed for this study, committee members were able to observe some of ARPA-E's efforts to recruit program directors. At five ARPA-E events—one workshop, three kickoff meetings, and the annual Energy Innovation Summit in 2016—committee members observed a similar recruiting pitch. At the workshop and kickoff meetings, the pitch was made at some point when all attendees were gathered and giving their attention to the speaker, the deputy director for technology. At the summit, the pitch was given during several of the scheduled sessions. The pitch consisted of the deputy director for technology informing the audience that ARPA-E is always seeking new program directors, asking anyone interested in applying to speak with him and/or send a resume, and asking anyone who knew of a potentially interested and qualified candidate to consider sending that person's resume. ARPA-E's website also lists program director as a current opening under the "job opportunities" link.[7]

Several former program directors presented information to the committee during open data gathering sessions. The committee also corresponded with several and consulted with others, and met with then-current program directors at ARPA-E events such as kickoff and annual meetings. Most program directors contacted for this study identified three common opportunities of serving as a program director that attracted them. First, they saw working at ARPA-E as presenting the chance to work with ideas and technologies that have the potential to be truly innovative. They found this as offering more chance to make a significant impact on the energy industry than

[7]As of May 15, 2017.

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working at some government research funding initiatives that they viewed as doing mostly incremental work and funding projects to develop well-known technologies along established roadmaps. They also contrasted ARPA-E with working in private industry, where research is focused on supporting existing product lines and over short time spans, leaving little chance to work on truly revolutionary ideas or technologies. Second, the research investment budgets that program directors must manage at ARPA-E—provided for establishing a focused technology program—are at least an order of magnitude greater than what they would expect to manage in private-sector settings. Even at the largest technology or venture capital firm, they reasonably would expect to be able to support 2 or 3 projects at a time; at ARPA-E, they could support roughly 20. On this scale, they believed they would have a real chance at making a significant technological impact in the sector. Third, the term-limited nature of the appointment meant that to make an impact, they would need to work hard on identifying and supporting promising ideas. They stated they found this a motivating factor, and contrasted it with the likelihood of building constituencies or maintaining independence from corporate or government bureaucracy that often accompanies long-term positions.

Although it could not draw any strong conclusions from these anecdotal observations, the committee found them enlightening and informative. A more systematic and in-depth analysis than was feasible during this study could make stronger conclusions. Given the descriptive statistics detailed above, however, many questions arise that either ARPA-E or an independent assessor would do well to attempt to answer. For instance, a review of the data on program director characteristics shows that fewer than 10 percent are or have been women. Whether this percentage is representative of the qualified talent pool available to ARPA-E or perhaps indicates some shortcoming in the agency's recruiting efforts, at least as measured by gender diversity, would be important to ascertain. Assessing such questions would require an unbiased characterization of the available talent pool, e.g., persons of sufficient education, experience, and talent, to use as a basis of comparison with the pool of applicants for program director positions. It would also need to include examination of practices such as outbound and inbound recruiting, likely with comparisons with effective industry practices of other public and private employers. Regardless of how the analysis might be conducted or who would conduct it, it would need to be carried out with ARPA-E's specific mission in mind, and with robust consideration of variables within ARPA-E's control and what labor market variables are beyond the agency's control.

Support of ARPA-E's Innovation Culture by Technology-to-Market Personnel

Every ARPA-E project is assigned a team, including a technology-to-market (T2M) advisor tasked with providing performers with non-technical assistance to help them prepare for eventual transition of the technology from laboratory to market. Most ARPA-E T2M advisors began their careers with technical or science degrees, adding an MBA or business experience later. The agency's goal is to attract personnel with direct technology experience who also have experience working with products and manufacturing so they can bring a supplemental, and sometimes different, perspective to bear on the thinking of the program directors. They work with performer teams to create technology-to-market milestones as part of award negotiation, and they work with the program directors to identify and encourage commercialization pathways during the award timeframe.

Given the long life spans of incumbent energy technologies, the relatively long timeframe and large amounts of capital required to adequately verify and validate new energy technologies

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and move them to commercial product development, there is an inherent tension between funding early-stage transformational technologies and bringing products to market quickly. It is unreasonable to expect that a technology could move from concept to market within the 3-year (or less) timeframe of an ARPA-E project. There is also a risk of ARPA-E's T2M team and the program directors becoming institutionally isolated from one another.

The committee was unable to conduct any quantitative analysis for T2M personnel as it did for program directors, but nonetheless was able to gather some qualitative data on these personnel, including their roles, functions, and activities. ARPA-E views its T2M activities as an ongoing experiment, and the challenge of developing such a program may be greater than originally thought. The T2M program was first created around 2011. At the time of this study the T2M program had 13 personnel and only a few alumni. Such a small sample could not be considered statistically representative, and any analysis would necessarily be subjective opinion.

In the evolution of T2M, ARPA-E needs to stay aware of two things. First, different performers have different needs. Small and young companies consulted for the case studies prepared for this assessment, especially those that spin out of university research, reported that T2M appears to work well (Appendix C). On the other hand, companies with marketing and commercialization experience reported that T2M provided little value to their projects (Appendix C). Second, technologies at different stages of development may have different T2M needs. For example, technologies at earlier stages of development could be burdened by milestones focused on attracting additional investment before project success is assured. One way to manage the inherent tension is to be aware of the different technology levels of different projects and stratify the T2M goals to match (Branz, 2015).

The committee recognizes the agency's efforts to continuously evolve and improve its T2M efforts and encourages further evolution while cautioning against overexpansion. For example, ARPA-E should consider making full T2M plans optional—encouraging development of these plans by performers most likely to benefit, such as academics—but requiring performers to describe potential product applications if they can prove technological feasibility. It also could provide information or research to performers on critical nontechnical factors that could impact market adoption of future products, such as regulatory risk and other, common risks other than business market risks.

A deeper analysis of the roles of T2M advisors and impact of the T2M program may be of great value to ARPA-E. Such an analysis was infeasible for this assessment, however, because of ARPA-E's youth.

Support of ARPA-E's Innovation Culture by Other Personnel

ARPA-E has a variety of staff that provide technical and commercialization support to its personnel. For example, much like DARPA, ARPA-E uses SETA contracts for relevant technical and nontechnical expertise. An example is a contractual arrangement with Booz Allen Hamilton (Booz Allen Hamilton, 2012). SETA contractors are intended to provide deep technical knowledge and also ensure smooth transitions when one program director's term ends and a new program director takes over a program. Depending on the needs of the program director and the project, these contractors can play an active role in a project.

ARPA-E also runs a fellows program that is intended to bring people to the agency very early in their careers and immerse them in the funding of high-risk and potentially transformative energy projects. During their tenure, fellows are expected to conduct technical and financial analyses to identify potential new technological opportunities, develop content for technical and

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other events, make onsite visits to performers, and perform other activities the agency expects will help identify new technological ideas to pursue and make connections with experts across fields and disciplines (ARPA-E, n.d.). The fellows program could be a good recruiting path for finding program directors. In fact, the agency expects that some of the fellows will be ARPA-E program directors within 10–15 years.[8]

The committee was unable to gather any data or conduct any analysis for support personal as it did for program directors and T2M advisors. One challenge is a concern that formally interviewing SETA contractors as part of an assessment may place them at risk of violating the prohibition on non-governmental personnel representing the government.

Autonomy's Importance for Effective Active Project Management

Providing autonomy for rapid learning and adaptation is a key element of active management within the DARPA tradition. Such practices align with evidence from the project management literature suggesting that allowing managers greater flexibility and autonomy in how they manage projects enables better outcomes from R&D. Uncertainty inherent in the innovation process reduces the real option value of an R&D effort, whereas extending the set of options available to a manager increases the option value (Huchzermeier and Loch, 2001). Similarly, Trigeorgis (1997) finds that the flexibility to adapt to new information improves the option value. Dixit and Pindyck (1994) show that efforts with more inherent uncertainty increase the value of managerial flexibility.

Research suggests there are two principal ways ARPA-E could empower its program directors and their technical staff with more flexibility to manage projects. First is to ensure that they have an adequate measure of *autonomy* (Amabile, 1998; Elkins and Keller, 2003; Ndubisi et al., 2015; West, 1990; Wynen et al., 2014). Autonomy is important because it provides flexibility in decision making, long known to be essential to promote innovation (Nelson, 1962). This is because a decentralized decision process empowers researchers to adjust quickly to results, respond to learning, and move quickly toward more productive paths (Nelson, 1962). Later empirical research has continued to support this idea, including at public-sector agencies in Europe with characteristics quite similar to those of ARPA-E (Amabile, 1998; Elkins and Keller, 2003; West, 1990; Wynen et al., 2014). Essentially, effective active management requires that program directors have autonomy in how they undertake that active management.

Second, ARPA-E can provide its program directors with resources and support to serve as *innovation champions* —clever, big-thinking, and future-oriented individuals who can imagine the possibilities in an idea and, importantly, also mobilize the resources needed to "explore, research, and build on promising, but uncertain, future technologies" and ultimately bring them to life (Tellis et al., 2009, p. 8; also, Berry et al., 2006; Howell and Higgins, 1990; Makri et al., 2006; Szczepańska-Woszczyna, 2015; Zenger and Lazzarini, 2004).

Evidence of Autonomy in Project Selection: Quantitative Analysis

Accordingly, a central question posed to this committee was the extent to which ARPA-E has internalized active management practices similar to those utilized by DARPA in its selection, management, and oversight of projects. The committee sought evidence that ARPA-E followed

[8]Interview with Mark Johnson.

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such practices, and directed its consultants to construct a large set of ARPA-E data from anonymized information on all concept paper applications; full-proposal applications; review scores for all full proposals; binary project selection; quarterly progress reports for each project; and outcome metrics associated with each project, including patent applications, publications, and a series of indicators for market engagement (e.g., follow-on funding) (the outcome metrics are presented in Chapter 4). For analysis of project outcomes, the dataset was then limited to the 234 completed projects as of December 2015.[9]

One critical component of a program director's job at ARPA-E is the design of a program and the cultivation of an applicant base for that program through engagement with experts in the field. As detailed in Chapter 2, the first step in the application process is the submission of concept papers. The dataset used for this analysis includes 10,227 concept paper submissions, 19 percent of whose authors were encouraged to submit a full application. The dataset used includes 2,335 submitted full applications,[10] 24 percent of which were selected for award negotiation. The overall selection rate resulting from this two-step application process was 5 percent.

Comparing the mean overall scores among all selected applications with the full distribution of scores in Figure 3-2 shows that the selected applications are not differentiated by their scores. The mean overall score for selected projects was 3.7 out of 5, compared with 3.3 out of 5 for nonselected projects. Ranking the applications in order of mean overall score within a program shows that ARPA-E frequently selected applications from across the full range of scores rather than systematically selecting the projects with the highest reviewer scores.

The selection rate varies significantly by program. OPEN programs receive more concept papers and full applications per available funding than focused programs. For OPEN programs,[11]

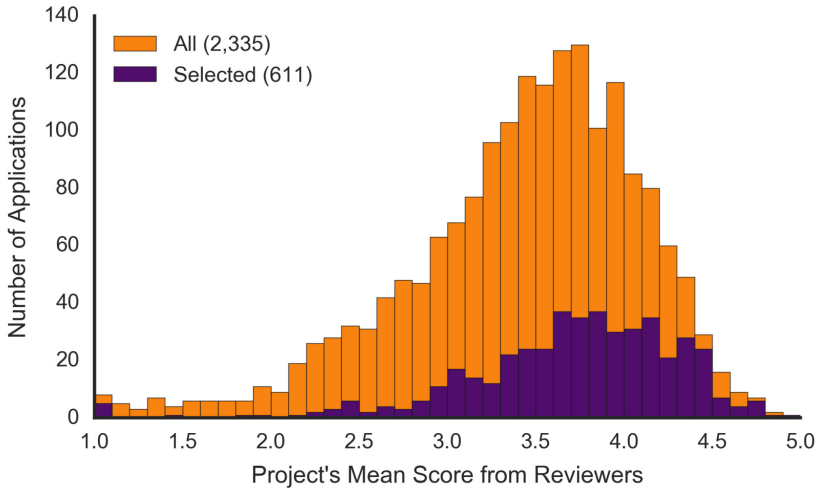

FIGURE 3-2 Mean overall scores of applications.

[9]Data collection began in January 2016.
[10]ARPA-E had initiated 471 projects by the end of 2015. Because the projects dataset was limited to completed projects, those projects that were active at the start of 2016 were excluded. The dataset then consisted of 234 projects with end dates on or before December 31, 2015.
[11]There is no data on concept papers from the first ARPA-E program, OPEN 2009.

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approximately 2 percent of the applicants that submit concept papers are eventually selected to negotiate for an award on average. Within the focused programs, on the other hand, approximately 11 percent of teams, on average, who submit a concept paper stage are eventually selected to negotiate for an award.[12] These average selection rates, however, mask the wide variation across different programs, ranging from about 2 percent for the OPEN programs, to approximately 30 percent for some of the focused programs.[13] Figure 3-3 shows the selection rate from concept paper through full application and on to selection for award negotiation for many of the programs that the committee's consultants were able to analyze. From full application to selection shows similar variation. The average selection rate for full applications is 24 percent, although the selection rate across programs ranges from 10 to 70 percent (see Figure 3-4).

As discussed in Chapter 2, at each step in the application process, external reviewers rate each application with respect to a variety of competencies, providing impact, merit, management, and overall ratings. The dataset for this analysis included reports for 1,800 of the 2,335 full applications. Each application had between 1 and 18 reviews, with a median of 3. Review scores ranged from 1 to 5, with a mean score of 3.4. However, there was wide variation in reviewer scores across many projects. For 20 percent of applications, the standard deviation for the overall score is greater than 1. Perhaps most interesting, the mean overall review score (or any other review category, for that matter) for each project had only a limited correlation with selection. This appears to support ARPA-E's statements that scores play a limited role in selection. Increasing a project's mean overall review score by a full point increased the likelihood of selection by only 20 percent. Moreover, holding mean overall review score constant, projects with a larger range of review scores were more likely to be selected. Given a constant perceived project capability, as shown by the average of reviewer scores, program directors were more likely to select those projects whose technical merit reviewers disagreed on, as shown by a larger spread between highest and lowest scores. This can be taken as evidence that ARPA-E is following its congressional mandate to identify and support projects with high potential for commercial and societal impact.

This analysis captures two important features of ARPA-E's project management that point to autonomy for program directors and other key personnel. First, ARPA-E's program directors have discretion to recommend projects for selection across the distribution of review scores according to their own discernment. The committee directed the consultants to create a counterfactual scenario whereby selection of projects for award negotiation was based solely on a numerical ranking of reviewer scores, with the highest-ranked projects being selected until the programs' funds were exhausted. For the purposes of this analysis, it was convenient to label these latter projects as having been "discretionarily selected." (See Box 3-1 for more detailed explanation of the process used for selecting which projects would be labeled as "discretionarily selected" for this analysis.) Almost half (49 percent) of ARPA-E projects can be labeled as "discretionarily selected" using the definition and process described in Box 3-1, a finding that serves as strong evidence of program director discretion in recommending projects for funding and agency autonomy in the final selection of projects to fund.

[12]Some FOAs requested full applications directly rather than soliciting concept papers as a first stage.
[13]Navy BEETIT is not included because it is a specialized program not representative of typical application requirements. It was a specific program for the Navy.

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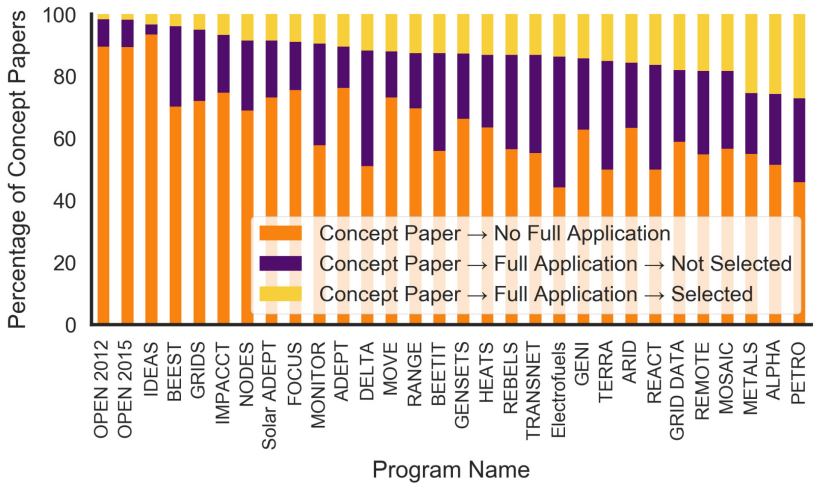

FIGURE 3-3 Percent of concept paper applications that result in selection for award negotiation.
NOTES: Data are percentage of 10,227 concept papers submitted to ARPA-E through December 31, 2015, by program. The SHIELD program is not included since it did not require concept papers. See Appendix D for a list of program acronyms.
SOURCE: Goldstein and Kearney, 2016.

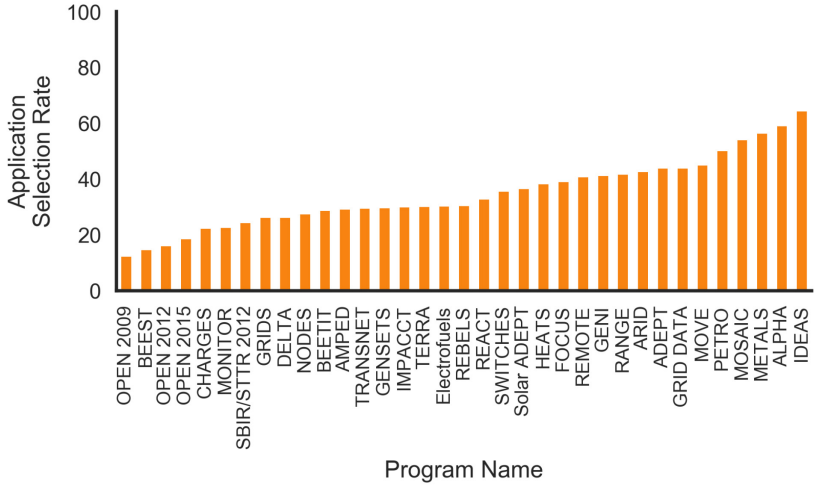

FIGURE 3-4 Selection of full applications by focused and OPEN programs.
NOTES: Data are percentage of 2,335 selected applications submitted to ARPA-E through December 31, 2015, by program. See Appendix D for a list of program acronyms.
SOURCE: Goldstein and Kearney, 2016.

Second, both selecting projects at the lower end of the review distribution and selecting projects that received a wider spread of reviewer scores are indicators of risk tolerance at ARPA-E, rather than peer review leading to regression to the mean. Program directors would be taking less risk if they made their funding recommendations by just picking the applications with the highest reviewer scores or based on reviewer consensus.

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BOX 3-1
Creating the Counterfactual Project Selection System

Using data on review scores for each selected application, the committee created an indicator variable to identify whether an application was selected based on program director discretion rather than a simple ranking of reviewer scores. The general method for identifying applications that were "discretionarily selected" from a low score was to create a counterfactual score cutoff, which would be used to determine selection if there were no program director discretion in making recommendations or agency discretion in making funding decisions. Selected applications with scores below this cutoff were labeled "discretionarily selected." For the analysis here, two cutoffs were created: (1) based on the number of projects selected and (2) based on the proposed budget for the Funding Opportunity Announcement (FOA).

In the first method, the number of applications selected under a given FOA was N. Then, the cutoff was placed at the Nth highest mean overall score. This method is illustrated in Figure 3-5. In the second method, the cumulative proposed budgets of the applications under an FOA were counted, starting from the highest mean overall score, and this count was then compared with the total budget listed in the FOA. When the cumulative budget reached the total budget for the FOA, the cutoff was placed at that score. For each program, the lowest of the two score cutoffs was taken, and the applications were labeled "discretionarily selected" if they received a mean overall score below this line. The "discretionarily selected" variable did not apply to OPEN programs, as they are recommended by many program directors across a range of technology types, and the projects are not compared directly.

Figure 3-5 illustrates the degree to which program director discretion was used within the RANGE program, as measured by the large number of discretionarily selected projects. As seen in Figure 3-6, the proportion of discretionarily selected applications across focused technology programs ranges from approximately 30 percent to 91 percent. One possible interpretation of this range is that program director discretion is not applied uniformly across programs.

Recent research supports ARPA-E's selection process as it balances the trade-off between valuable information to be gained and potential bias that comes with peer review. Reviewers may assign lower scores because of bias against novel ideas, the very thing ARPA-E needs to identify. A randomized controlled study found that "evaluators systematically give lower scores to research proposals that are closer to their own areas of expertise and to those that are highly novel," with patterns consistent with "biases associated with boundedly rational evaluation of new ideas" and inconsistent with "intellectual distance simply contributing 'noise' or being associated with private interests of evaluators" (Boudrea et al., 2016, p. 2765). At the same time, peer review can still be of value. For instance, one study of National Institutes of Health (NIH) granting activity found a "one–standard deviation worse peer-review score among awarded grants [to be] associated with 15% fewer citations, 7% fewer publications, 19% fewer high-impact publications, and 14% fewer follow-on patents," even with detailed controls for an investigator's publication history, grant history, institutional affiliations, career stage, and degree types (Li and Agha, 2015). There is also evidence of the value of external information in making decisions. For instance, one study found that employees hired by manager discretion despite lower scores on a hiring test had lower retention rates than those who scored higher (Hoffman et al., 2015).

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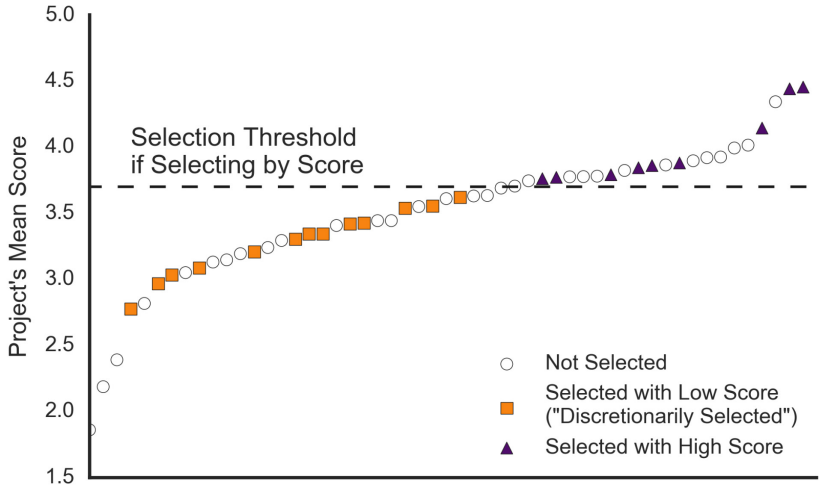

FIGURE 3-5 Evidence of program director discretion in project selection (RANGE program): Projects selected with a high score and discretionarily selected projects.
NOTE: Discretionarily selected projects are those that would not have been chosen using a simple ranking by reviewer score (see Box 3-1 for more detail).
SOURCE: Goldstein and Kearney, 2016.

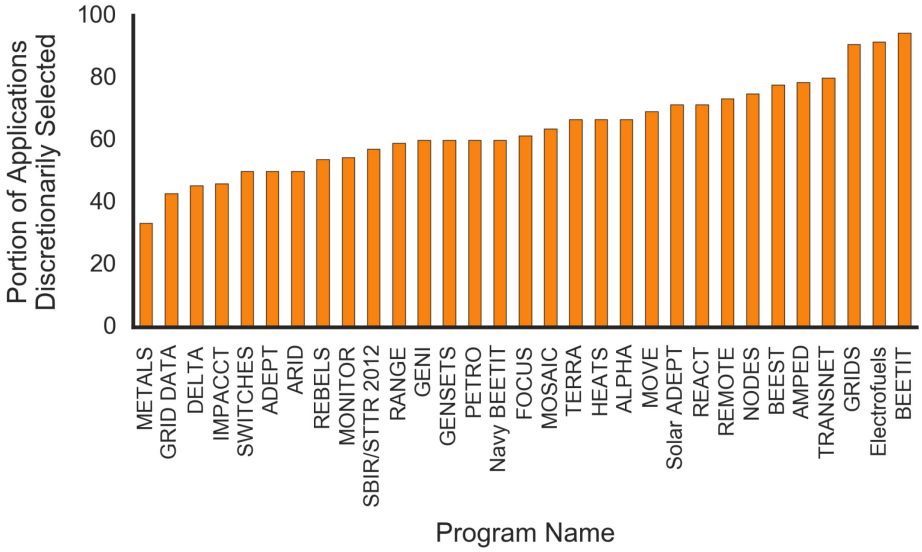

FIGURE 3-6 Program director discretion in project selection, by focused program: Portion of projects with a low score that were discretionarily selected.
NOTE: Discretionarily selected projects are those that would not have been chosen using a simple ranking by reviewer score (see Box 3-1 for more detail). See Appendix D for a list of program acronyms.
SOURCE: Goldstein and Kearney, 2016.

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These findings appear to support ARPA-E's decision to seek valuable information from peer reviewers while retaining program director discretion. The agency's merit review process appears to account for possible biases in reviewer scores that can actually help with making the most use of them as one possible guide to locating truly novel ideas.

Performance of Discretionarily Selected Projects

Having determined that this discretion exists, a natural follow-up question arose regarding the performance of projects on the lower and upper ends of the review score distribution. Although the sample size of completed projects was too small for regression analysis, there has been no evidence to date that the discretion accorded to program directors results in poorer outcomes as a result of their selecting some projects with lower average review scores. It is possible that because discretionarily selected projects likely involve higher risk, their average performance over time will be similar to that of non–discretionarily selected projects. It is also possible, however, that over time, the distribution of outcomes may be wider, with more successful outliers—big winners—and more abject failures (i.e., the practice of promoting projects leads to a mean-preserving spread in outcomes). However, a larger dataset derived from a longer time series would be needed to observe this phenomenon, so that more time would have to pass for these dynamics to occur and be observable. Consequently, it would be useful to consider this possibility in future reviews of ARPA-E.

Active Project Management: Quantitative Evidence

Once projects have been selected for funding, each project team enters a negotiation phase with ARPA-E during which the parties agree upon financial terms and project-level milestones. Funding levels and project lengths vary significantly across projects. The award amount averages $2.3 million, with a maximum of $9.1 million. Initial project lengths vary from two quarters to 4 years. Also during the negotiation phase, the performer and program director agree on technical milestones and tasks. Once agreement has been reached on the funding level, timeline, and milestones, project work begins.

ARPA-E requires that performers submit status reports and meet with program directors on a quarterly basis. These interactions are not simply a formality—project direction, funding levels, and continuation are at stake each quarter. Program directors rate the progress of each project using stoplight colors (red, yellow, or green), and quarterly report data confirm that budgets, milestones, and project lengths are often modified. On average, budgets are increased by $0.2 million, and projects extended by 0.5 year. In some cases, though, projects are terminated early, as was the case for 23 of the 234 completed projects analyzed for this study.

Conversations with performer teams and with ARPA-E technical staff, including program directors and systems engineering and technical assistance (SETA) support staff, strongly suggest that a common component of active project management is to modify milestones in response to data generated through the course of a project. At least as often as each quarterly review, and often more frequently, project performer teams converse with the program director and his or her technical team. During these meetings, the performer teams provide data on progress toward meeting quarterly milestones. Rather than simply noting "yes, the milestone was met," or "no, the milestone was not met," the technical staff are trying to assess and understand what the project performer team has really learned. In a case where one or more milestones were not met, the program director attempts to work with the performer team to understand why. If it

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was not met because it was too technically ambitious, then performer and program director are likely to discuss modifying the milestone's technical target, modifying its due date, or eliminating it if it is unlikely to be achievable during the life of the project. If milestones were met, the program director may investigate whether the milestones were not ambitious enough, perhaps modifying later milestones to be more technically ambitious or to be met earlier in the project's life. Program directors and performers will also create new milestones in response to the feedback and data.

At least 45 percent of projects experience at least one milestone change. Likely this is an underestimate because the data available capture only deletion or creation of milestones during the project, and not a technical change or a due date change within a milestone. Support staff are responsible for coding changes into an administrative database. The database, however, lists only creations and deletions; there is no separate flag for modification. It is clear that sometimes when a milestone was modified, the technical target was updated, but within the database the "old" milestone was not deleted and replaced with a "new" one incorporating the updated criteria.

For this analysis, projects were further subdivided into two groups based on the percentage of measured quarters that involved milestone creation or deletion. Slightly more than one-fourth (28 percent) of projects had "infrequent" milestone changes (milestones changed in fewer than 25 percent of the measured quarters), and 17 percent had "frequent" milestone changes (milestones changed in 25 percent or more of the measured quarters, i.e., at least once per year). The distribution of projects among these groups is illustrated in Figure 3-7.

Project Assessment to Inform Active Management: Quantitative Assessment

Each quarter program directors rate projects according to how well they are meeting their milestones for technical, cost, schedule, and overall performance. In 2015 an additional milestone was added to track technology-to-market performance. (Technology-to-market advisors are discussed in the next section.) The ratings are given as either green, yellow, or red, where green means the project is on track and meeting milestones; yellow means the project has missed milestones but can recover; red means the project has missed significant ("go/no-go") milestones and may not be able to recover. Examining the data on overall status for all project

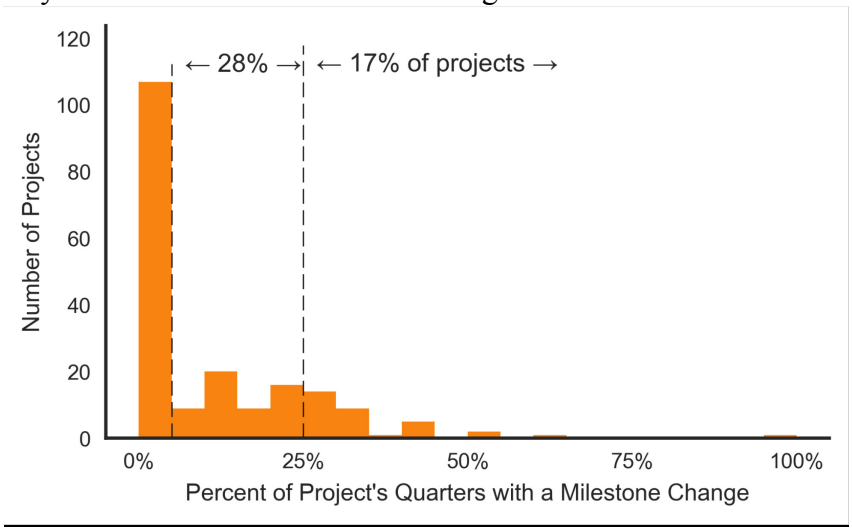

FIGURE 3-7 Frequency of milestone creations and deletions.
SOURCE: Goldstein and Kearney, 2016.

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quarters, 55 percent of quarters were rated green, 38 percent yellow, and the remaining 7 percent red. Table 3-1 shows a transition matrix depicting the dynamics of changing colors from one quarter to the next. The table reveals a high degree of rating persistence. Green ratings are especially stable (78 percent chance of persisting), followed by yellow (71 percent) and red (66 percent). Positive changes in status are relatively more likely than negative changes. For example, there is a 21 percent chance of a yellow status becoming green, compared with an 8 percent chance of a yellow status becoming red.

Considering the trajectory of projects through different status ratings, green ratings are seen to be frequent across the dataset. A majority of projects (88 percent) had at least one overall green quarter, and a majority (61 percent) never had a red quarter. Furthermore, 9 percent of projects were overall green for their entire duration. Focusing on the final quarter, all but three terminated projects ended with an overall red status, likely because the most common reason for early termination is failure to meet milestones. By comparison, a much smaller portion of projects that went full term ended on a red status. There were also some projects with consecutive red quarters that later changed status and were able to go to full term. One possible reading of these data is as additional evidence of program director discretion. For example, if ARPA-E had a bright line rule, say, requiring termination of any project with two consecutive red quarters, then it is possible that program directors would be required to terminate projects for nontechnical reasons such as a principal investigator's suffering from an acute but short-term medical condition or a family emergency that temporarily slowed or halted work. But while the project management dashboard rating system is based on much information, it is still not the total picture of a given project. Thus, even in a situation where a project has successive red status quarters, the program director can determine whether there is a path for the project team to rectify whatever led to missing targets and still complete the project in good standing instead of recommending that the project be terminated. Such discretion can provide positive outcomes.

Goldstein and Kearney found a number of correlations between milestone changes and quarterly status ratings. Although it is difficult to determine whether or not the quarterly project status changes because of milestone changes, Goldstein and Kearney (2016) find that a "quarter in which a project is rated 'green' is 2-3% more likely to be a quarter in which milestones were added or deleted, compared to a 'red' or 'yellow' quarter." An analysis that could draw conclusions, rather than just correlations, regarding causation between milestone changes and quarterly status would require analyzing which milestones were changed, such as whether technical, cost, schedule, technology-to-market, or overall performance, and why the change was made. Although ARPA-E keeps track of the category of milestone changed, to conduct this analysis they would also need to record systematically two other attributes of the milestone changes. First, there would need to be a detailed record of precisely why milestones were

TABLE 3-1 Transition Matrix for Overall Status

		$Status_{t+1}$			
Status		Red	Yellow	Green	Total
$Status_t$	Red	66%	29%	5%	100%
	Yellow	8%	71%	21%	100%
	Green	1%	21%	78%	100%

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changed. Second, there would need to be a control group of some sort that could be used to build a counterfactual, but creating a control group for participants in a government program is extremely difficult.

Nonetheless, the data that are available regarding quarterly interactions illustrate an element of active project management within ARPA-E, capturing the hands-on nature of program directors' engagement with each project and the project performer team. This is evidence that active program management is taking place and satisfying Congress's requirement that program directors recommend restructuring or termination as needed.[14] It also points to the third defining organizational feature of ARPA-E listed earlier: that active project management is important to ARPA-E.

Examining this body of evidence led to the identification of the second defining organizational feature of ARPA-E listed earlier: that ARPA-E program directors maintain significant autonomy and discretion in project selection and management.

Processes to Support a Culture of Innovation and Risk Taking

ARPA-E has in place a number of processes intended to support achieving its mission and goals. This section describes human resource processes for program directors and analyzes the impact of PD transitions. It also describes ARPA-E's cost sharing requirements and processes for awards.

Program Director Transitions

Given the importance of the program director in shaping focused technology programs and managing projects, the committee investigated the potential for disruption when program directors change. Given program directors' potential impact on projects, hiring top-tier talent is a necessity for the success of ARPA-E programs. The agency's authorizing legislation set the standard term for program directors to 3 years, presumably seeking an appropriate balance for program directors who must weigh the prestige of being a program director against the forgone salary and career progression had they not taken a break from a nongovernmental position. Program directors spend the first 12 to 18 months of their tenure managing projects from existing programs following departure of another program director, designing programs, and soliciting projects. They spend the balance of their term managing the new projects created in their program, along with any other assigned projects. Since project lengths typically range from 2 to 3 years, many projects will experience a change in program director.

A majority of projects examined for this analysis (70 percent) experienced at least one program director change. The number of program director changes was 0.89 on average and the median was 1.0, meaning that the typical project experienced one such change. A measure of the rate of program director turnover was obtained by scaling the number of program director changes by the length of the project. The mean value for turnover was 0.3 changes per year, and the distribution among all projects is shown in Figure 3-8. Projects that experienced program director changes are divided into two groups: one with "low turnover," which experienced at least 1.0 change but less than 0.5 change per year (49 percent of projects), and one with "high

[14] 42 U.S.C. 16538(g)(2)(b) (2017).

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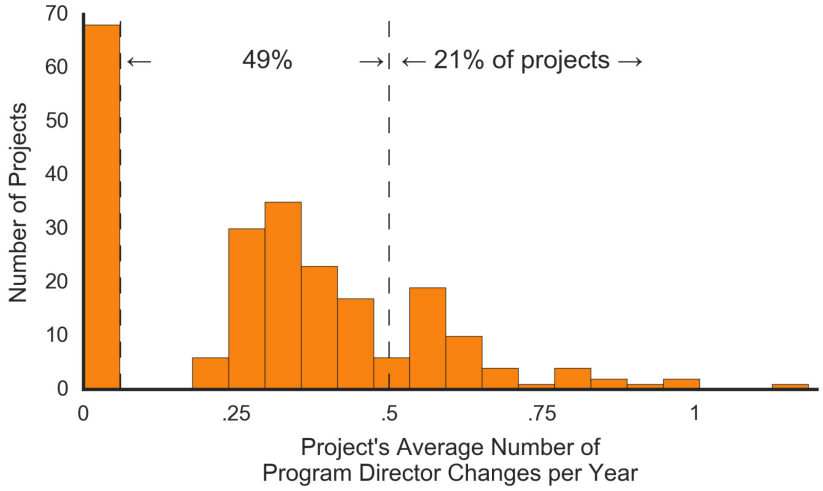

FIGURE 3-8 Frequency of program director changes across projects.
SOURCE: Goldstein and Kearney, 2016.

turnover," defined as 0.5 change per year or more (21 percent of projects). The remaining 30 percent of projects did not experience a program director change.

One might expect that a program director transition could negatively impact a project through the loss of management continuity. Yet the committee found no evidence that projects have been harmed by such transitions, even after controlling for other variables. First, Goldstein and Kearney (2016) show that there is no significant relationship between program director transitions and ARPA-E's internal metric of project success. In other words, after controlling for organization type, initial award amount, and initial project length, there is no relationship between a project's having had at least one program director change and the project's having been terminated early, ending up with a status of green (meeting all milestones), or ending up with a status of red (failed to meet milestones) (Goldstein and Kearney, 2016, Table 10). Furthermore, after controlling for organization type, initial award amount, and initial project length, the likelihood of a project's filing a patent application increased if the program director changed (Goldstein and Kearney, 2016, Table 17).

Cost Sharing

Congress mandated that ARPA-E's program directors identify "innovative cost-sharing arrangements for ARPA-E projects."[15] Consequently, cost sharing is a requirement for obtaining an ARPA-E award, although a variety of waivers are available. One rationale for cost sharing is that it requires ARPA-E awardees to become financially invested in their projects. Another is that it allows leveraging of federal dollars; particularly for projects intended to lead to commercialization of the technology, it can help ensure the involvement of partners capable of moving products to market. Cost-sharing minimums vary depending on the requirements of the particular FOA, but are typically either 5 percent, 10 percent, or 20 percent if the project is awarded under a cooperative agreement or grant. If a project award is made through a technology

[15]42 U.S.C. 16538(g)(2)(B)(v) (2017).

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investment agreement or an "other transaction" agreement, the minimum cost-sharing obligation is typically 50 percent of the total project cost.

The committee heard statements that cost sharing can be problematic, and some individuals stated that it acts as an impediment to the participation of national laboratories and small companies in ARPA-E programs and projects. Some present and former ARPA-E employees questioned the value of the cost-sharing component in the context of the ARPA-E model. One former program director observed that the intrinsic purpose of cost-sharing requirements is to leverage federal funds and to ensure that industry participants have genuine interest in conducting research in a given technology area. In contrast, another former program director stated the belief that cost sharing yields few benefits, has various unintended negative consequences, and may already be seen by private companies as a disincentive to applying for ARPA-E funding.[16]

The Energy Policy Act of 2005 (EPACT 2005) provides authority for DOE, and thus ARPA-E, to modify or reduce cost-sharing requirements.[17] For example, such modifications have also been adopted in the Office of Energy Efficiency and Renewable Energy (EERE), where an awardee can request a reduction in the cost share from 20 percent to 10 percent. Each of ARPA-E's FOAs outlines cost-sharing requirements for project budgets, including the possibility of applying for a modification of those requirements.

Comparisons to and Coordination with DARPA, Other Offices at DOE, and Other Federal Agencies

Because ARPA-E was patterned after DARPA, many of the agency's processes have their origins at DARPA. While other DOE offices have utilized some processes and practices similar to those found at ARPA-E, since the agency's creation, some offices have taken steps to adapt ARPA-E's processes to their own contexts in a more systematic fashion.

Comparisons to DARPA

Many of ARPA-E's attributes and processes were inspired by or borrowed from DARPA, although there are key differences as well. Both, for instance, are meant to be autonomous within their respective cabinet-level departments and feature relatively low levels of hierarchy. Other key areas of similarity include an organizational culture of risk taking, a focus on hiring highly qualified technical staff with academic and industrial backgrounds, and providing broad autonomy for program managers/directors to identify and support relevant technologies for specific purposes. There also are some important differences, though, in the agencies' attributes and how they undertake their work.

The largest and most important difference is the size of each agency's budget and the uncertainty surrounding whether it will be funded. The disparity in budgets leads to a number of critical differences in each agency's overall approach to funding research. DARPA's annual budget is roughly 10 times that of ARPA-E and, as part of the Department of Defense, is not under threat of being reduced to zero each year. This scale and certainty of funding allows DARPA to take a broad and long-range view and approach to supporting technology innovation

[16]Presentation to the committee by Dane Boysen, December 8, 2015.
[17]42 U.S. Code § 16352.

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that ARPA-E cannot take. This characteristic of DARPA manifests in several ways. First, the agency has always featured offices focused on specific technological areas. These offices are often organized with particular strategic initiatives in mind, and they are directed to create and fund programs that support over multiple decades the entire suite of technologies needed to provide platform support for the desired technological outcome rather than to fund individual technologies.

DARPA also has a long history of holding "summer studies" that bring together its program managers and leading scientists and engineers to study and review future research areas. Participants engage in activities aimed at fostering better understanding of current military challenges and establish task forces to focus on potential new directions and programs at DARPA that can help meet these challenges. Afterward, DARPA program managers continually engage with the research and innovation community, meeting with researchers and users to keep learning about emerging research, capabilities, and needs. They deliberately seek to direct research toward solving a challenge or creating a capability by seed-funding researchers working on common themes. They fund multiple, often competing or disconnected researchers with an aim of nudging the research in a particular direction and increasing knowledge flow within the research community. DARPA's offices will support activities and focused funding programs to pursue meeting a strategic challenge for as long as doing so makes sense, often for decades.

Many of these kinds of strategic activities would be difficult for ARPA-E to undertake because of its much smaller budget. As noted earlier, each year when new programs are funded, to mitigate the risk that its budget may be reduced to zero, ARPA-E obligates from that year's appropriation the full amount of funding needed to create and fund its projects for their full duration, often 3 years. Coupled with its existential uncertainty, ARPA-E has little capacity to pursue the sorts of long-term strategic activities that DARPA undertakes as described above. Similarly, ARPA-E has yet to utilize such mechanisms as inducement prizes or grand challenges.

The agencies have quite similar approaches to reviewing applications and selecting projects for award negotiation. Both request pre-proposal submissions and then encourage some entrants to submit full applications. Both agencies ask that these submissions take the form, effectively, of a response to the Heilmeier Catechism.[18] Both review full applications through program director/manager-driven processes. DARPA, however, does not utilize peer review in its process because of concerns that peer reviewer comments or scores tend to discount truly novel and potentially breakthrough ideas. ARPA-E's merit review process, on the other hand, makes use of information from peer reviewers, especially written comments, although evidence presented in Figures 3-5 and 3-6 show that many projects are "discretionarily selected."

Another area of commonality between ARPA-E and DARPA is making use of two different types of programs to fund research, ones focused on a specific technology or technology area, and so-called open announcements seeking any good idea that fits within the agency's mission. There is a significant and technologically consequential difference in the way that each agency conducts its call for submissions. At DARPA, each program office has a standing announcement that is always available for submissions, even if the idea does not align with current technology-specific programs. This allows office directors and program managers to fund worthwhile ideas whenever an innovator is capable of submitting. ARPA-E's OPEN FOAs, however, are offered only every 3 years and accept submissions for only a set period of time, usually about 90–120

[18]The Heilmeier Catechism refers to a set of questions created by George H. Heilmeier, director of DARPA from 1975 to 1977, to help agency officials think through and evaluate proposed research programs.

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days. Consequently, innovators who have an idea for a submission outside of that time window must wait until another OPEN FOA is announced, possibly as long as 3 years. It is unlikely that the ARPA-E could adopt an open system like DARPA's without a larger budget and less budgetary uncertainty.

Table 3-2 summarizes the most significant points of comparison between ARPA-E and DARPA.

Comparing ARPA-E's Mission and Goals with Other DOE Research Offices and Programs

Although ARPA-E funds some projects that fall within broad categories of technologies also funded in other parts of DOE, it funds specific research ideas or individual technology ideas that are out of scope, at different stages of development, or have different risk profiles for other parts of DOE. The Office of Science focuses its support on fundamental scientific research. The applied offices make their applied research investments hew closely to technology roadmaps that appear less risky, with the expectation of continuing their investments in particular technologies or programs over long periods of time across many stages of the innovation cycle, from pilot projects through large-scale demonstrations and on to late-stage deployment, although they also fund applied research (EERE, 2015). In contrast, ARPA-E's funding announcements inform potential applicants that the agency funds "applied research and development" as defined by the Office of Management and Budget. Its funding announcements have also directed readers to contact the Office of Science if their project is for basic research, while directing those with "projects focused on the improvement of existing technology platforms along defined roadmaps" to consider seeking support from one or more of DOE's applied offices (ARPA-E, 2015a). As seen in Figure 3-9, there is evidence that ARPA-E funds projects mainly at technology readiness levels 2 to 4, as reported by the performer teams in their full applications.

As one example of the differentiation between ARPA-E and research funded by other parts of DOE, in 2010 ARPA-E launched a program focused on novel materials and processes for postcombustion carbon capture technologies for gas- or coal-fired power plants. The program's technical overview expressly stated that it sought to complement decades of "existing DOE research efforts in the field of CCS [carbon capture and storage]" (ARPA-E, 2010b, p. 1). DOE's CCS roadmap explained that its efforts funded "a large number of laboratory-scale and pilot-scale research projects involving solvents, sorbents, membranes, and oxygen combustion systems" for coal-fired power plants, but not for gas-fired plants (DOE, 2007, p. 16). In contrast, projects in the ARPA-E program included new approaches on membranes and sorbents, sponges, biological enzymes, cryogenics, and other potential solutions that were not being considered by DOE. After reviewing the data and results from the ARPA-E-funded projects, the Office of Fossil Energy funded 3 (out of 15) of the projects (NETL, n.d.). This supports the view of ARPA-E as a connector or in-between funding source for ideas that are transitioning from the laboratory to the applied offices or later-stage private funding (DOE, 2014).

Operational Differences with Other DOE Programs and Their Adoption of ARPA-E Practices

The qualitative data gathered through consultations with individuals from DOE and ARPA-E clearly indicates that ARPA-E and other DOE offices do attempt to coordinate efforts, even though as yet this occurs through informal and ad hoc channels rather than through a formal process or institutionalized channel. There is no office of coordination, nor is there a special advisor to the secretary for coordination of funding offices within the department.

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TABLE 3-2 Comparison of Attributes of DARPA and ARPA-E

Attribute	DARPA	ARPA-E
Agency Organization		
Direct Report to Department Secretary	Yes	Yes
Flat Organizational Structure	Yes	Yes
Agency Features		
Focused Mission	Yes: initiate rather than be the victim of strategic technological surprises	Yes, technologically narrower: overcome the long-term and high-risk technological barriers in the development of energy technologies
Budget Size	Approximately $3 billion/year	Approximately $280 million/year
Concentrated Primary Market	Yes: Department of Defense and prime contractors, but for many sectors no longer the dominant source of demand	No
Number of Program Managers	Nearly 100	Approximately 15
Term Appointments for Program Mangers	Yes, 3-5 years	Yes, 3 years
Culture an Important Feature to Support Mission Success	Yes	Yes
Technical Offices Focused on Relevant Technology Areas	Yes: office managers orchestrate a "pyramid of technologies" across programs	No: agency budget too small
Set Aside Full Multiyear Project Funding in Year One	No: annual appropriations sufficiently certain to enable annual allocations	Yes: to mitigate uncertainty of future budgets
Procedures and Processes		
Orchestration of Technology Directions	Yes: specific strategy for all office directors and program managers in support of achieving technical outcomes and agency mission	Aspirational, but not yet a specific strategy

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Attribute	DARPA	ARPA-E
Funding of Entire Platform of Technologies Necessary to Achieve Particular Goals	Yes	No: budget too small
Program Managers/Directors Have Autonomy in Funding Recommendations	Yes: no peer review	Yes: program directors utilize information from peer review, but are not obligated to follow score cutoff or "rack and stack"
Effort to Build New Research Communities	Yes: specific strategy for all office directors and program managers in support of achieving technical outcomes and agency mission; aim is to connect previously disconnected researchers to enable otherwise infeasible research	Unclear: at present, ad hoc with anecdotal evidence
Active Management of Projects	Yes	Yes: regular site visits, review of data with performers, suggestions regarding technical directions of research and project team
Go/No-Go Technical Milestones for Projects	Yes, but how much has varied by decade and program	Yes: legislatively required; quarterly review of progress toward achieving milestones and feasibility
Program or Procedures to Ensure Awardees Plan/Prepare for Eventual Commercialization	Yes: focused on military application; Adaptive Execution Office seeks to accelerate transition from DARPA project to Defense Department capability; focus on commercializing for defense with increasing interest in dual-use potential; most applications envision some application of technology; expectation that good technologies and teams will find new funding sources to continue past DARPA granting period since "DARPA is not in the business of sustaining the technology"	Yes: specific program and personnel to assist awardees with orienting to eventual market entry, identifying commercial applications, and finding sources of funding to continue past ARPA-E award period
Intensive Gatherings of Entire Research and Innovation Community to Identify Priorities and Directions	Yes: intensive problem-focused gatherings of thought leaders to determine specific problems to solve	No

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Attribute	DARPA	ARPA-E
Inducement Prizes and Competitions, and Grand Challenges	Yes	No, presumably because of budget limitations
Program Features		
Programs Focused on Specific Technical Outcomes with Measurable Goals	Yes	Yes
Broad Area or Open Programs to Capture Promising Ideas That Do Not Fit within Particular Focused Programs	Yes	Restricted: OPEN program is made available roughly every 3 years, with an application window of approximately 120 days
Fund Competing Technologies Aimed at Solving the Same Problem	Yes	Yes
Project Management Features		
Suggest Milestone Modifications Based on Findings from the Project		Yes
Regular Contact with Research Teams	Yes	Yes, at least quarterly.
Suggest Milestone Modifications Based on Findings from Other Projects across Program and Agency		Yes
Suggest Teaming Partners		Yes
Suggest Changes in Personnel or Subcontractors		Yes

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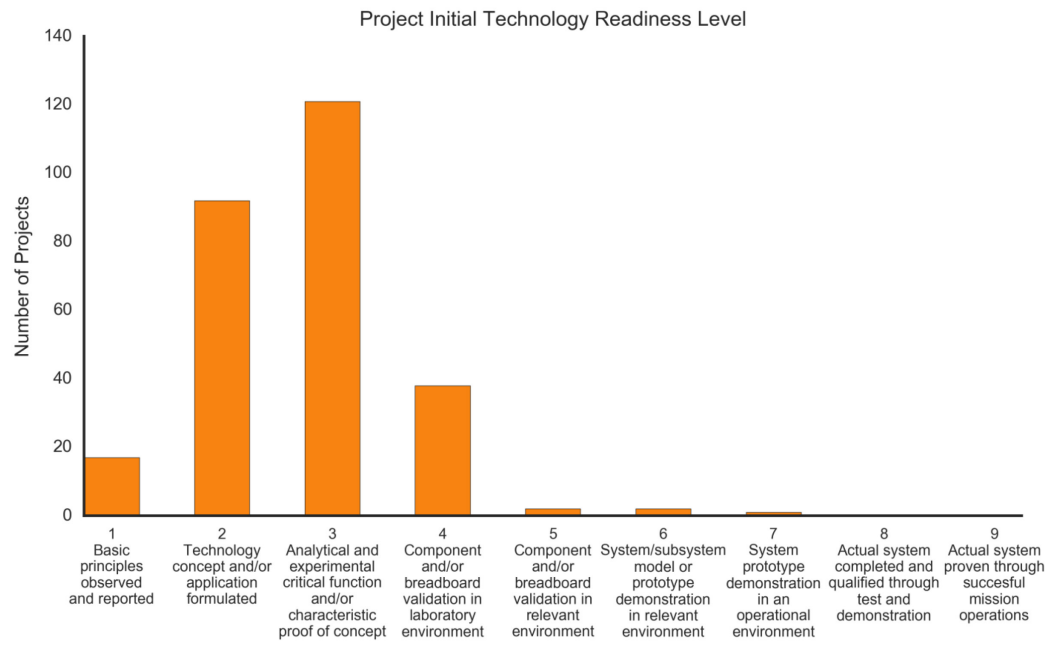

FIGURE 3-9 Technology readiness level of projects funded by ARPA-E.

The T2M advisors on a project work to provide information on potential private-sector or government funding to performers following the end of their ARPA-E funding period. They learn of potential leads for both private funding and potential DOE applied office funding for performer teams from coordination with other DOE offices, although the bulk of that knowledge comes from their own direct engagement and networking with private funders. Much as with program creation and funding decisions, when it comes to technology transfer, there is coordination with the rest of DOE but through informal channels, and thus far in ad hoc ways closely associated with individual program directors.

Coordination is necessary because of operational and programmatic differences between the two. One operational difference between ARPA-E and DOE's energy research offices is the approach they take to developing programs. Although all of the offices have funding opportunity announcements, the processes they use to select and manage projects differ from ARPA-E's. Since the research offices of DOE are not exempt from federal civil service hiring law and regulations like ARPA-E, they may have difficulty attracting highly qualified talent to oversee offices and research programs.

Some of the other DOE offices have begun to adapt several of ARPA-E's operational procedures for their own use. Many DOE program leaders expressed interest in ARPA-E's congressionally provided authority to be nimble and flexible. Some have adopted certain of its ideas and approaches, as described below for EERE, and the Office of Electricity Delivery and Energy Reliability (OE), while others such as the Office of Fossil Energy (FE) have not.

Office of Energy Efficiency and Renewable Energy ARPA-E develops its programs and projects in close consultation, primarily informal, with EERE. EERE administers a risk-adjusted portfolio of long-term efforts to achieve goals that could not be attained in the absence of government support. This longer-term view is necessary to accomplish EERE's mission.

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ARPA-E looks at EERE's portfolio of projects, notes where EERE is doing work, and identifies white spaces in which ARPA-E projects could complement what EERE is doing in such areas as grid-scale power storage and batteries for electric vehicles. ARPA-E's program directors and EERE's program managers coordinate these efforts without formal institutional support. A 2011 assessment of ARPA-E found that the agency had "met with success in forging a working alliance with EERE, a much larger $1.5 to $2 billion a year applied agency. ARPA-E has EERE experts on its review teams and draws on that expertise; it has received strong support as well from EERE's leadership, who are working with ARPA-E" to demonstrate and further develop technologies, and to connect them to potential private or other public funders (Bonvillian and van Atta, 2011, p. 491).

EERE has studied and adopted a number of ARPA-E practices (with minor adaptations). These include (1) using FOAs and similar processes for selecting and funding proposals, such as pre-proposals similar to ARPA-E's concept papers; (2) holding workshops to convene experts; (3) empowering program managers to make funding recommendations; (4) using cooperative agreements that can be terminated; (5) engaging in active program management, including go/no-go decisions (ability to terminate projects); and (6) having the ability to create and adjust technical milestones that inform go/no-go decision making.

The Vehicle Technology Office (VTO) and the SunShot Initiative are two examples of EERE's efforts to adapt ARPA-E practices to improve office and program effectiveness and efficiency. VTO was quick to use concept papers as the first stage in applying for funding under an FOA, utilize an adapted form of ARPA-E's evaluation criteria, and seek to ensure that reviewers are considering the potential impact of a successful project in addition to its technical merit. The SunShot Initiative borrowed those same features along with the use of SETA contractors for technical expertise support.

One reason EERE has attempted to adopt and/or adapt various procedures from ARPA-E is that after departing ARPA-E, some program directors were hired at EERE in leadership roles. Former program director Mark Johnson, for example, took leave from his academic position to direct EERE's advanced manufacturing office. David Danielson, ARPA-E's first program director, became the Assistant Secretary of Energy Efficiency and Renewable Energy in May 2012. He informed the committee that he intentionally chose not to attempt to remake EERE to look just like ARPA-E. Rather, he worked to adapt processes and procedures that could work within EERE's mission and institutional framework. Key among these were empowering program managers to select awardees for grants, hiring some key personnel under limited terms, actively managing awards, and funding awards using cooperative agreements with specific milestones so the awards can be terminated early if they cannot meet those milestones.[19]

Office of Fossil Energy An FE representative stated that "coordination between FE and ARPA-E has been poor and partial. Despite several face-to-face discussions between FE and ARPA-E and interest from both sides in several topics (e.g., advanced carbon capture technology or water treatment or reuse), they have not yet converged. As such, we have had no joint workshops, no joint solicitations, no coordinated launches, and no road mapping. While there is a benefit in such activity, to date they have not begun." When asked if there are aspects of the

[19]Consultation with David Danielson, Assistant Secretary for Energy Efficiency and Renewable Energy, DOE, 2015.

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ARPA-E operations that can (or should) be transferred to the rest of DOE, the FE representative replied "no."[20]

Office of Electricity Delivery and Energy Reliability OE has close, regular ties with ARPA-E staff. OE staff attend ARPA-E workshops and help with the evaluation of proposals to ensure that ARPA-E awards do not duplicate work already under way at OE. OE staff also attend ARPA-E peer reviews and annual program director meetings for projects. OE program managers work closely with ARPA-E in the areas of grid modeling and energy storage to ensure that each entity selects complementary projects, with ARPA-E emphasizing more aggressive goals and OE being more concerned with achieving larger scale.

OE has attempted to adapt certain ARPA-E practices, although it is hampered by its own budgetary, personnel, and operational constraints. OE, like ARPA-E, has sought to improve coordination with other offices at DOE, the result being the development of stronger solicitations. ARPA-E has demonstrated to OE how to build stronger projects, create more competition within projects (instead of using an existing set of stakeholders), and bring together larger groups from which to solicit proposals and evaluate projects and solicitations. OE, like ARPA-E, is now funding multiple projects rather than merely the top ones in particular topic areas. An OE representative observed that the relationship between the research underwritten by OE and ARPA-E could be improved if the two agencies consulted with each other before their respective project solicitations were issued.[21]

OE is interested in ARPA-E's process for developing solicitations, which includes constructive confrontation and vigorous internal debates. The OE representative observed that the competitive process leads to very strong solicitations on the ARPA-E side. It is more difficult, however, for OE to adopt such practices because, unlike ARPA-E program directors who are with the agency for 3 years, OE program managers typically have been with the office for a very long time and have developed constituents, inhibiting robust debate.

Comparisons with Other Federal Departments and Agencies

ARPA-E engages with over 70 organizations and agencies within the federal government. Most of those are within other offices at the Department of Energy. The agency also engages with various defense offices, including DARPA, as well as the Department of Homeland Security, the National Aeronautics and Space Administration, the National Science Foundation, the National Institute of Standards and Technology, and the Department of Agriculture (Williams, 2015). The committee was unable to investigate fully ARPA-E's coordination with federal agencies beyond DOE.

[20]Based on answers to written questions from the committee obtained from Christopher Smith, Assistant Secretary for Fossil Energy, DOE, 2016.
[21]Interview with Patricia Hoffman, Acting Assistant Secretary for Electricity Delivery and Energy Reliability, January 6, 2016.

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SUMMARY OF FINDINGS AND RECOMMENDATIONS

ARPA-E's Culture, People, and Processes

Finding 3-1: ARPA-E program directors have been empowered to take risks in project selection in line with the agency's mission.

Finding 3-2: Program director discretion enables ARPA-E to fund relatively risky projects, with no indication that average project performance in the short term is reduced.

Finding 3-3: Program directors are continuously engaged in ongoing projects, as reflected by the altering of project milestones, budgets, and timelines, to help ensure that projects support ARPA-E's mission and goals.

The results of the committee's quantitative and qualitative analyses indicate that ARPA-E has internalized the principles of an innovative culture, dynamic leadership, and program director autonomy in its organizational structure. Specifically, ARPA-E program directors exert significant autonomy and discretion in program creation and project selection and remain actively engaged in managing projects on a quarterly basis through milestone revisions, budget modifications, and timeline adjustments. ARPA-E also appears to have positive spillover effects on other offices in DOE, especially EERE.

These findings highlight the important role of the program directors in ARPA-E's continued vitality and in enabling the agency to execute its mission and goals. Program directors join ARPA-E because they believe that they can make an impact that they could not by working in private industry or academic settings. Their limited tenure and freedom to pursue ideas with potential to have a large impact empowers them to bridge market failures and create value that can help ensure that the "United States maintains a technological lead in developing and deploying advanced energy technologies."[22]

Recommendation 3-1: ARPA-E should preserve its distinctive and flexible management approach that empowers program directors and stresses active project management.

Recommendation 3-2: ARPA-E should continue to hire exceptional program directors and empower them to create programs and manage projects.

Reconceptualizing Technology-to-Market

Finding 3-4: ARPA-E considers its "technology-to-market" (T2M) activities to be an ongoing experiment, and the challenge of developing such a program may be greater than originally thought.

[22] 42 U.S.C. 16538(c)(1)(B) (2017).

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As discussed previously, given the long life spans of incumbent energy technologies and the relatively long timeframe and large amounts of capital required to adequately verify and validate new energy technologies and move them to commercial product development, there is an inherent tension between funding early-stage transformational technologies and bringing products to market quickly. It is unreasonable to expect that a technology could move from concept to market within the 3-year (or less) timeframe of an ARPA-E project. The value added by this part of ARPA-E's project management varies by project and performer. Some performers consulted during this study, in particular those with established product development and marketing capacity, did not find ARPA-E's current approach for T2M helpful.

The committee recognizes the agency's efforts to continuously evolve and improve its T2M efforts and encourages further evolution while cautioning against overexpansion. For example, ARPA-E should consider making full T2M plans optional—encouraging development of these plans by performers most likely to benefit, such as academics—but requiring performers to describe potential product applications if they can prove technological feasibility. It also could provide information or research to performers on critical nontechnical factors that could impact market adoption of future products, such as regulatory risk and other, common risks other than business market risks.

Recommendation 3-3: ARPA-E should reconceptualize its "technology-to-market" (T2M) program to account for the wide variation in support needed across programs and performers with respect to prospective funding, commercialization, and deployment pathways.

Processes to Support a Culture of Innovation and Risk Taking

Finding 3-5: The program director hiring policies at ARPA-E appear to complement the agency's programmatic timelines. Many projects experience a program director transition, but on average, this transition is not detrimental to project performance.

Perhaps a necessary by-product of hiring top-tier talent will continue to be program director transitions. These transitions do not appear to have negative impacts on project performance and may be beneficial. This was seen when, even after controlling for performers' organization type, initial award amount, and initial project length, the likelihood of a project's filing a patent application appeared to increase if the program director changed. These findings will become more specific as the sample size increases in subsequent assessments. In addition, the qualitative analysis could be converted to a survey or other quantitative form to improve the coverage of and further enhance the findings presented in this chapter.

Recommendation 3-4: ARPA-E should continue its practice of hiring program directors for 3-year terms, allowing for one, term-limited extension when necessary to complete implementation of a new program or for other reasons determined by the ARPA-E director.

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Transferring ARPA-E's Programs and Processes to Other Parts of DOE

Finding 3-6: ARPA-E is a positive agent of change in DOE and the federal government, and its best practices are being adopted in some DOE offices. ARPA-E's role as a positive change agent has been facilitated by its outreach and bridge-building efforts with respect to other federal organizations since its formation.

While there are important differences in the missions and goals of other DOE offices and ARPA-E, those other offices can still learn from ARPA-E's business practices. DOE has long been known for a bureaucratic culture. In contrast, ARPA-E is widely seen as having a nimble, efficient, and innovation-supporting culture. Several DOE offices have adapted some ARPA-E practices in an effort to improve their own operations. Notably, EERE has begun using practices and procedures to (1) use FOAs and similar processes for selecting and funding proposals; (2) hold workshops to convene experts; (3) empower program managers to make funding recommendations; (4) use cooperative agreements that can be terminated; (5) engage in active program management, including go/no-go decisions (ability to terminate projects); and (6) have the ability to create and adjust technical milestones that inform go/no-go decision making. Adopting such practices can go a long way toward reducing bureaucracy and improving operational efficiency and excellence. Doing so will increase the efficacy of the programs and their value to the American people.

Recommendation 3-5: The secretary of energy should ensure that other offices and programs within DOE continue to explore and adopt elements of ARPA-E's practices that can improve the department's operations.

Recommendation 3-6: ARPA-E and DOE should provide incentives to encourage more interaction between other DOE program offices and ARPA-E, which could potentially help reduce DOE's bureaucratic culture.

Project Selection at ARPA-E

Finding 3-7: ARPA-E selects projects to fund through a multifaceted process that entails evaluating each project's potential to contribute to the achievement of the agency's goals should it be successful.

Quantitative evidence demonstrates that ARPA-E has instituted a system focused on finding and funding ideas with a high potential for impact on achievement of the agency's mission and goals. The evidence also shows that this system involves a numbers of stages, and that at each stage ARPA-E uses a multifactor process to make decisions regarding applications. This process emphasizes technical assessments from internal and external reviewers; applicants' responses to those comments; and a holistic assessment of funding recommendations that considers the technical content of the applications, the potential for impact on achieving agency goals should projects be successful, and nontechnical factors. The process addresses such important issues as portfolio balance, both across technical categories and within the funded program, with an eye to ensuring sufficiently varied approaches. This process is distinguishable from those of other

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agencies that do not allow for as much program manager discretion in individual funding decisions or use a more rigid system such as basing funding decisions principally or solely on numerical reviewer scores, often ranking applications by scores and utilizing a strict cutoff that does not allow for discretion on the part of the agency or program directors. Strong and consistent evidence indicates that projects selected through ARPA-E's process have the potential to yield measurable outcomes at least as good as, if not better than, those of projects that would have been selected had less discretion been allowed.

Even though it is still too early to measure accurately the long-term technological impact of this system, it clearly was designed with mission success in mind rather than sticking with tradition. Additionally, when considered together, findings 3-6, 3-7, and 3-8 suggest that ARPA-E has thus far maintained its independence from such constituencies as groups seeking funding. Implementation of several of this report's recommendations, particularly Recommendations 3-1 and 4-3 and 4-8 (in Chapter 4) would help ensure that ARPA-E maintains its independence both within and outside of DOE by interested constituencies.

Program Directors and Authority

Finding 3-8: ARPA-E program directors have wide authority to develop new focused technology programs that are potentially transformative.

The committee consistently found both qualitative and quantitative evidence that ARPA-E's program directors are empowered with wide authority in carrying out their responsibilities, including those outlined in the agency's authorizing statute. Program directors create new technologically focused programs through a process that encourages novel ideas with the potential to identify and promote revolutionary advances or translate discoveries into technological innovations. This process involves collaboration and critical review with the agency director, other program directors, and the wider research community, and encourages the pursuit of ideas overlooked or ignored by other funders, as well as truly novel ideas.

Finding 3-9: ARPA-E program directors actively manage projects through technical research guidance and feedback, regular and frequent assessments of progress made toward stated technical milestones, and revision of milestones in response to new findings and research discoveries.

Throughout a program's life cycle—from review of applications, through award negotiations, to project completion—program directors engage in active program management. They work closely with project teams to create milestones, which can be modified in accordance with what the team learns through the course of its research. Program directors can, and do, recommend personnel changes and work with performers to identify and recruit qualified personnel or subcontractors. They regularly engage with performers to discuss a project's technical approach and collaborate to revise it based on results to date. They also recommend that performers modify their research approaches when appropriate, including pivots or more significant project restructuring. And they recommend that the agency terminate funding early when projects repeatedly fail to meet their milestones and appear unlikely either to do so in the future or to pivot to milestones that are achievable.

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4

Technical Assessment

The statement of task for this study (Box 1-1 in Chapter 1) directs the committee to conduct a retrospective assessment and technical evaluation of ARPA-E, including the most significant accomplishments and impacts of the ARPA-E program and any unique features of the program that may have contributed to these accomplishments. In undertaking this assessment, the committee considered the stated goals of ARPA-E, how those goals might be measured, and the impacts of the agency's projects and programs. There are clear indicators that ARPA-E is making progress toward achieving its statutory mission and goals, and it cannot reasonably be expected to have completely fulfilled those goals given so few years of operation and the size of its budget.

With respect to ARPA-E's stated goals, this chapter begins by explaining two terms that are key to those goals—transformational technologies and white space. The chapter then describes the external metrics used to assess impacts of ARPA-E programs and projects. Next, the chapter presents the results of the committee's technology assessment: evidence of the impact of ARPA-E programs and projects based on three key external metrics—scientific publications, patents, and market engagement; evidence of impact from the case studies conducted to support the technology assessments (see Appendix C); and the agency's impact on transforming energy industry attitudes, creating new communities of researchers, and improving public awareness of its achievements. As with its approach to the operational assessment reported in Chapter 3, the committee used multiple methods for this technology assessment, which are described in detail in Appendix B. The chapter ends with a summary of the findings resulting from the committee's technology assessment and its recommendations for moving forward.

ARPA-E TECHNICAL OBJECTIVES: TRANSFORMATIONAL TECHNOLOGIES AND WHITE SPACE

Chapter 1 describes how ARPA-E was created to turn revolutionary advances and out-of-the-box ideas into transformational energy technologies to reduce energy imports and emissions, improve efficiency, and ensure that the United States maintains a technological lead in advanced energy technologies. The agency also describes itself as looking to fund projects that fill "white space"—energy technologies not being fully addressed by the private sector or other federal research programs (ARPA-E, 2013a; Rohlfing, 2015). For this study, transformational technologies and white space were defined as described below.

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Transformational Technologies

The congressional authorization of ARPA-E includes a mandate that the agency accelerate transformational technological advances but provides no guidance on the meaning of the term. ARPA-E describes its own mission as to "catalyze and accelerate the creation of transformational energy technologies" through high-risk, potentially high-reward investments, and often uses the term "transformational" in its program descriptions (ARPA-E, 2014a).

ARPA-E does not offer a specific, concise definition of the word transformational, but it does state that it seeks to fund research with the *potential* to identify new technology learning curves with potential to lead to technologies with performance/cost ratios significantly greater than incumbent technologies (ARPA-E, 2013b). For any technology, energy or otherwise, whether or not one of these curves will produce truly transformational technologies, in most cases, can be recognized only in retrospect,[1] after the specific technology has matured enough to disrupt its market by being more widely adopted than incumbent technologies, or by creating an entirely new market. Often the specific details—cost, performance, application, size and scope of market, specific impact on society—look different from what was imagined when the technology is in its early development stages.

Figure 4-1 provides illustrative examples of the unpredictability of technology disruption in terms of the performance/price ratio over time for common information storage technologies. In the mid-1980s, looking at the curve for magnetic tape since 1950, it would not have been immediately clear that its performance to price ratio would overtake the incumbent technology, printed material. Following several decades of slow improvement, the gains appeared to have leveled off before overtaking printed material. By contrast, around the year 1970 magnetic disk technology appeared to be on a fast trajectory to disrupt, having already outperformed magnetic tape on a trend that suggested it would soon overtake printed material, too. For the next 15 years, though, magnetic disk technology made only modest gains and still lagged behind printed materials. Both technologies, however, did eventually outperform printed material by the mid-1990s, after over 40 years of development. Punch cards and optical disks tell different stories of unpredictability. When first introduced, punch cards provided much less storage per dollar than printed materials. They showed some improvement over time, but never caught up to the incumbent technology or the newer technologies that entered the market. Optical disks started at a high performance to price ratio which quickly rose.

[1]There are exceptions in which the potential for technologies to be transformational was recognized in advance. The first p-n junction solar cell, discovered circa 1954, was hailed at that time by *The New York Times* (1954, April 26), which states that the silicon solar cell "may mark the beginning of a new era, leading eventually to the realization of one of mankind's most cherished dreams—the harnessing of the almost limitless energy of the sun for the uses of civilization." A second example is the switch from bipolar junction technology (BJT) to metal-oxide-semiconductor field-effect transistors (MOSFETs) for high-end computing. Today all servers are MOSFET based, whereas prior to 1993, every powerful mainframe was BJT based. The IBM CEO at the time, Lou Gerstner, bet on the projected progress in MOSFETs predicted by Moore's Law for this transformation to put IBM ahead of its competitors, such as Hitachi. A third example is the search for blue light emitters. Researchers in the early 1990s knew that an efficient semiconductor light emitter or laser in the blue would be transformational. GaN turned out to be that material, and it revolutionized lighting. In all instances, though, several decades passed before the technologies' full impact could be observed, and such impact has been seen only in retrospect.

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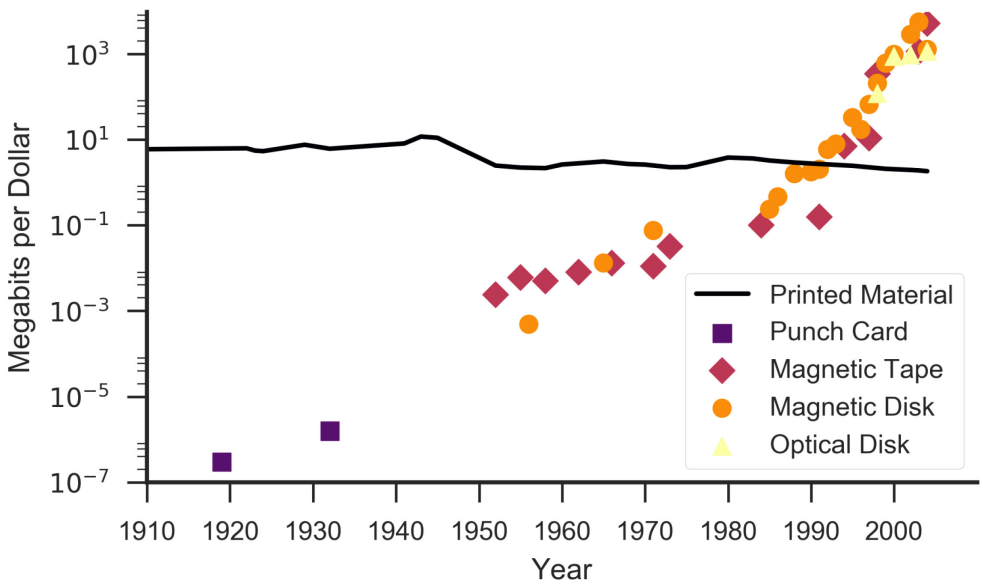

FIGURE 4-1 Plot of performance per cost from 1910 to 2010 for common information storage technologies.
SOURCES: Koh and Magee, 2006; data hosted on pcdb.santafe.edu, Nagy et al., 2013.

Overall, all of the technologies appeared to have disruptive potential when introduced. But only optical disks outperformed printed material when first introduced. For the rest, whether or not they would prove to be transformational only became evident in retrospect after 40 years or longer.

This helps in understanding that ARPA-E's core philosophy of supporting transformational research is properly viewed as supporting projects that have the *potential* to be transformational. The project or program that holds the real potential to be transformational must be structured to seek forks in the technology roadmap, such as the multiple technologies shown in Figure 4-1, and must challenge the conventional understanding of what is possible, practical, or profitable in impactful applications. Such a project also can shake up industrial or political establishments. One way ARPA-E assesses the potential for a program or project to be transformational is to evaluate it against a version of the Defense Advanced Research Projects Agency's (DARPA) Heilmeier questions (Rohlfing, 2016).

For this assessment, then, the committee developed a set of questions to use in determining whether a program or project is potentially transformational:

- Does the program/project hold potential to create "forks" in the technology roadmap that could change the conventional understanding of what is possible, practical, and profitable in applications with large potential impact?
- Does it reach for impacts that may be very far off but that may eventually result in faster learning curves and potentially disruptive entitlements?
- Does it bridge gaps in technological development that might otherwise prevent a particular research pathway from being advanced?
- Does it challenge a community to tackle barriers seen as too risky for rate of return–based investment decision metrics?
- Does it empower a community to challenge conventional wisdom regarding feasibility?

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- Does it shake up "group think" and political or industrial establishments?
- Does it set aggressive targets that, if attained, could result in high impact?
- Does it create a stakeholder or technical constituency?
- Does it revisit a failed approach in the context of related supporting advances or changes in economic or other external factors?
- Does it fuse disparate technologies in novel ways?

White Space

In developing and reviewing proposed programs, ARPA-E personnel make it clear that the agency seeks to fill white space as it develops and reviews its proposed programs (e.g., Rohlfing, 2015). Funding of white space is intended to address a perceived gap or opportunity in the energy technology landscape. As discussed in Chapter 2, searching for white space for ARPA-E entails pursuing energy technology innovation with two distinct but related objectives: the search for technological approaches that are truly novel or greatly underexplored, and the search to fill gaps left in other research or funding programs. Figure 4-2 shows how the Full-spectrum Optimized Conversion and Utilization of Sunlight (FOCUS) program addresses white space.

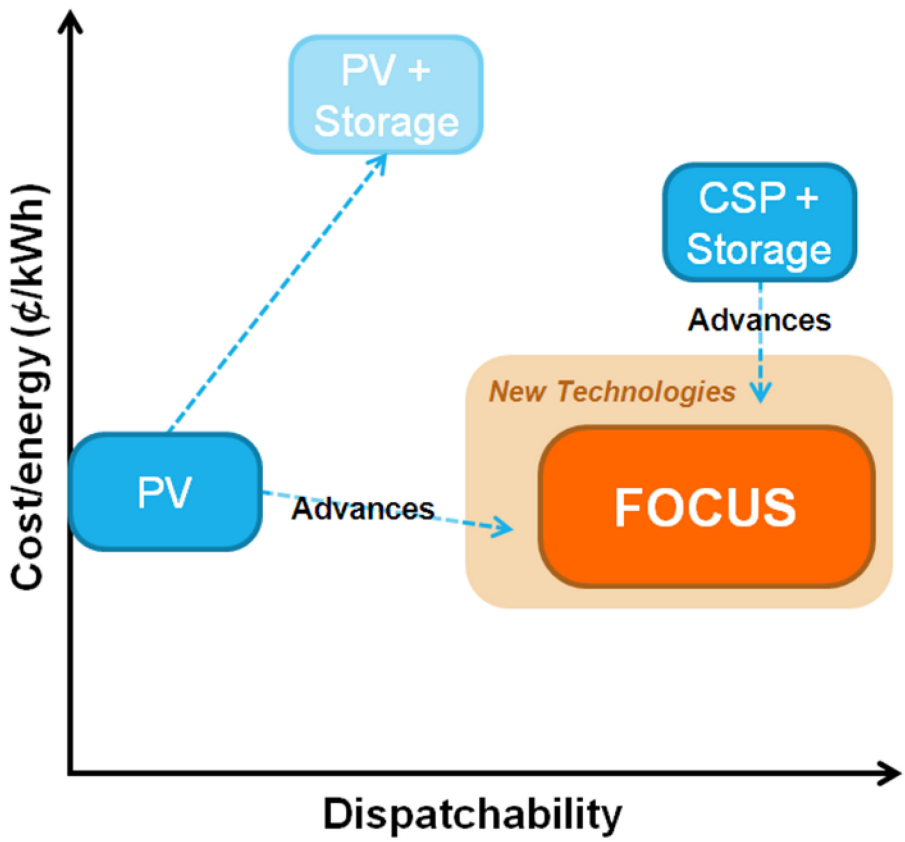

FIGURE 4-2 White space addressed by the Full-spectrum Optimized Conversion and Utilization of Sunlight (FOCUS) program.
NOTE: CSP = concentrating solar power; PV = photovoltaic.
SOURCE: Rohlfing, 2015.

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While the distinction is not explicitly described by ARPA-E, the committee notes that funding white space technologies may or may not necessarily be the same as funding transformational technologies. This distinction is apparent in reviewing the breadth of ARPA-E's programs. Clearly, some of ARPA-E's programs—such as the Strategies for Wide bandgap, Inexpensive Transistors for Controlling High Efficiency Systems (SWITCHES) program for developing advanced semiconductor materials or the Batteries for Electrical Energy Storage in Transportation (BEEST) program for developing dramatically better batteries for plug-in electric vehicles—are aimed at potentially transformational energy technologies. But other programs—such as the Advanced Management and Protection of Energy storage Devices (AMPED) program for improving battery management controls and sensors and Generating Realistic Information for the Development of Distribution and Transmission Algorithms (GRID DATA) program for developing open-access electricity system models, datasets, and data repositories—address a more specific technological challenge. These latter programs are about funding ideas in white space areas that are perceived to be overlooked by other parts of DOE, other agencies in the federal government, and private companies. Such projects may not necessarily be pursuing technologies with high likelihood of being truly transformational but rather filling a critical technological need that could help enable the development of such technologies.

Importance of Balancing Expectations

Given that truly transformational technologies, whether in the energy or some other sector, take many years or decades before becoming apparent and that ARPA-E has existed for only 6 years, the committee would not expect any ARPA-E programs to have had any transformational impacts on the energy sector yet. As discussed in subsequent sections, however, discernable intermediate outcomes provide indications of the potential for success. It is often impossible to gauge what will prove to be transformational; tests or breakthroughs that garner big headlines can end up being underwhelming in the long run, whereas small, incremental tweaks can turn out to enable major shifts in technologies or processes. More fundamentally, it is unclear whether all projects within the ARPA-E portfolio should be targeted to transformational technologies. Rather, keeping in mind the distinction drawn above, funding projects that fill a white space may also produce results consistent with the agency's objectives and help enable transformational energy technologies.

EXTERNAL METRICS USED TO ASSESS OUTCOMES

The statement of task for this study directs the committee to examine processes, deliverables, and metrics used to assess the short- and long-term success of ARPA-E programs. In her presentation to the committee, then director of DARPA, Arati Prabhakar, offered a cautionary note that there are "no viable metrics for judging success" for an agency seeking to bring about transformational innovations (Prabhakar, 2015). However, federal funding of energy technologies receives more scrutiny than defense-related funding, and any technical evaluation of ARPA-E must rely to some extent on metrics. While recognizing that all metrics are imperfect, then, the committee used the quantitative and qualitative metrics described in Box 4-1 in conducting its technology assessment of ARPA-E.

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BOX 4-1
Description of Metrics for Technology Assessment of ARPA-E Used in This Report

- **Publications:** Publications weighted by citations or journal impact factor can provide a metric of research output. However, publications are peer-reviewed, and the most novel scientific contributions do not necessarily get published in the top journals, given the limitations of scientific institutions, the publication process, and peer review (see, for example, discussions in the management field by Barnutek and colleagues [2006]; Daft and Lewin [2008]; and Alvesson and Sandberg [2012]). Eventually, citations can reveal the importance of novel research, but this could take decades if the work is ahead of its time. Thus, not all performers do or should have journal publications as a primary objective of their project.
- **Patents:** Patents can provide a measure of research output. They can be quality weighted through citations and claims (Hall et al., 2001, 2005; Griliches, 1998; Lanjouw and Schankerman, 1999). Because citations can be added by examiners as well as inventors, citations may be a poor measure of knowledge flows (Alcacer and Gittelman, 2006; Roach and Cohen, 2013; Moser et al., 2016). Because patenting rates differ by industry and context, magnitudes of patenting or citations cannot be compared across contexts. Further, recent work suggests that only 42 percent of new-to-market manufacturing products are patented (Arora et al., 2014), and it is known that process innovations are more likely to be held as trade secrets and not to be patented (Cohen, 1995; Cohen and Klepper, 1996). Finally, not all performers are or should be trying to conduct research with immediate, patentable commercial value.
- **Follow-on funding:** Follow-on funding, which may come from other federal or state agencies, venture capitalists, or other investors, may be a good metric to assess technologies supported by ARPA-E as long as the full range of follow-on funders can be identified and tracked. Notably, this is not to say that no project should receive funds more than once from ARPA-E. Certain technologies may need additional funding from ARPA-E before private or other public investors are willing to invest in the technology. For example, it could be provided to continue to advance the science to the point that others pick up and take over. Alternatively, such follow-on funding might be to fund DARPA-like scale demonstrations. This could, however, require decades and multiple performers, depending on the broader context in both the innovation ecosystem and the marketplace. For example, DARPA has been funding alternative materials to silicon complementary metal-oxide-semiconductors (Si-CMOS) for decades because such alternative materials have relevance in certain military contexts, but it is only in the last few years that Si-CMOS's remaining runway has become sufficiently short to garner industry attention and funding (Khan et al., 2014).
- **New firm development:** In addition to follow-on funding, the formation of a new start-up company following support by ARPA-E is an important metric of market impact. Like with patents and publications, not every project should have firm formation as its immediate goal. Some projects may lead directly to formation of new firms while others will only plant the seeds for firms to form around the technologies supported well past the project timeline.

NOTE: In addition to these metrics, the technical and other milestones created and adjusted through a project are discussed in Chapter 3.

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The success of individual programs and projects cannot be determined by a single metric—different projects by definition have different goals and thus different outcomes. Nor, given the wide diversity of project objectives, are there metrics that are appropriate for all projects. And in many cases, outcomes will be difficult to measure. ARPA-E funds different organization types and different technology areas that require different assessment metrics. Funding academic institutions may result in more publications, whereas funding small companies may lead to more patents. Large companies may be more interested in using project results internally; in such cases, outcomes as measured by external metrics may be less substantial, but internal impacts on the company may be greater in the form of providing validity or encouraging a new direction. Further, different technologies will differ in their feasibility and scale and in the funds required for prototyping and demonstration.

The committee was interested in developing systematic metrics for the social, economic, and environmental impacts of ARPA-E projects, but given the relatively short timeframe being assessed and the small number of projects that have achieved downstream market engagement, the committee did not believe there would be measurable evidence with which to conduct assessment against the program's long-term objectives. As noted in Chapter 2, the goals for ARPA-E include reducing imports of fossil fuel, reducing energy-related emissions, and ensuring that the United States maintains a technological lead in the development and deployment of advanced energy technologies. Nonetheless, ARPA-E has completed more than 200 projects, and these projects provide a record of early accomplishments. Accordingly, the following sections review some of the intermediate impacts of ARPA-E projects and programs according to key external metrics described in Box 4-1 and the case studies conducted to support this assessment, keeping in mind that the passage of decades may be required for the ultimate successes of the work funded by ARPA-E to become manifest. A longer discussion of other metrics that could be used to undertake a retrospective assessment of ARPA-E's technology is included at the end of this chapter.

EVIDENCE OF OUTCOMES FROM ANALYSIS OF KEY EXTERNAL METRICS: SCIENTIFIC PUBLICATIONS, PATENTS, AND FOLLOW-ON FUNDING AND NEW FIRM FOUNDATION

As discussed above, the committee's central task was to assess the impact of projects funded by ARPA-E given the relatively short timeframe that has elapsed since the agency began operating. ARPA-E provided the committee with aggregate information on some intermediate outcomes of the work it has funded. As of midyear 2015, 581 journal articles and 74 patents had acknowledged ARPA-E funding (Williams, 2015). At the 2016 ARPA-E Energy Innovation Summit, the agency announced that 45 projects had secured more than $1.25 billion in private-sector follow-on funding, 36 projects had led to the formation of new companies, and 60 projects had partnered with other government agencies for further development (ARPA-E, 2016a). The agency has also begun to compile and publish examples of intermediate outcomes at the project and portfolio levels (ARPA-E, 2016b). In particular, the agency has developed project impact sheets that include the intellectual property and publications from selected projects in grid storage and operations, power electronics, transportation, clean energy, and efficiency. The same report also describes the results from the portfolio of projects and programs in stationary energy storage.

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To derive further insight, the committee worked with an external consultant to undertake in-depth analyses based on the metrics described in Box 4-1. Data from ARPA-E was augmented as described in Appendices B and F. This analysis gave the committee insight into both the incidence of observable outputs from ARPA-E projects and the sources of variation in these outputs across programs and types of organizations funded.

The committee directed the consultant to undertake two interrelated analyses summarized in Goldstein (2016). First, Goldstein analyzed the scientific publication and patenting outputs of ARPA-E projects relative to research projects funded by other U.S. Department of Energy (DOE) agencies, most notably the Offices of Science and Energy Efficiency and Renewable Energy (EERE) (Goldstein, 2016).[2] This analysis leveraged the fact that ARPA-E is one of many DOE entities that fund research, development, demonstration, and deployment for energy-related technologies. Among these funding entities, ARPA-E has a unique mission—to explore high-risk, potentially high-reward ideas within the energy landscape—and unique operational capabilities for executing this mission. Despite these unique characteristics, however, there are agencies within DOE that support early-stage basic and applied research with which ARPA-E can be compared. Specifically, research conducted within the Offices of Science and EERE bears the greatest resemblance to that funded by ARPA-E. Second, Goldstein examined variation among ARPA-E projects and considered the role of organization type (e.g., university versus start-up versus established firm) and project characteristics (e.g., the program with which the project is associated) in explaining that variation. For this latter analysis, it was possible not only to look at publications and patents but also to leverage ARPA-E's own public data reporting on the external market engagement of its projects.

While the committee recognizes that these offices have different missions both from each other and from ARPA-E, these analyses help demonstrate ARPA-E's productivity to date and how the agency can contribute to DOE's overall mission to develop and deploy innovative energy technologies. They show that ARPA-E has produced intermediate impacts that demonstrate progress toward accomplishing its ambitious goals.

Scientific Publications

Goldstein (2016) performed a detailed analysis of the impact of ARPA-E relative to that of the Offices of Science and EERE using a dataset of all awards offered by the three agencies. This dataset links award-level specifications for recipient type, amount of funding, and project length to publicly available outcomes credited to each award. The sample includes data on patents, patent quality, publications, and publication quality, which, while not completely informative, are appropriate measures for innovative output for purposes of this comparison. For publications (and patents in the following section), the author evaluated both the likelihood of producing at least one output and the incidence rate for producing a number of outputs. The analysis controlled for award amount, project length, awardee type, and fiscal year in which the award was made, all of which can impact the rate of publishing and patenting. A number of important observations with respect to publication output emerged from this analysis.

First, ARPA-E projects were more likely to publish and to do so with high frequency relative to other DOE offices. Recipients of 44 percent of ARPA-E awards published at least once, compared with the Office of Science and EERE at 27 percent and 18 percent of awards, respectively. In fact, ARPA-E awardees were three times as likely to publish as EERE awardees.

[2]As discussed in Appendix B, Goldstein excluded national laboratory-led projects.

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Importantly, this latter finding is robust to the inclusion of control factors, such as the amount of funding awarded and project duration. After controlling for these observable differences, however, ARPA-E awardees had the same rate of publishing as Office of Science awardees. ARPA-E awardees received significantly more funding than Office of Science awardees on average, and their projects were slightly longer in duration, which led to a higher percentage of ARPA-E projects that published.

In addition to this baseline result, Goldstein (2016) found significant differences in the nature of these publication outputs. Specifically, ARPA-E awards resulted in more publishing in top journals[3] relative to EERE awards and in more energy journals relative to Office of Science awards. (ARPA-E awards published in top journals at the same rate as Office of Science awards and received an equivalent number of citations.)

Of course, ARPA-E's objectives go beyond the publication of scientific papers, and many projects of a potentially transformative nature may never engage in the scientific publication process as part of their market and social impact. Further, research shows that the probability that a paper is cited peaks years after its publication, that the median lag from publication to patent citation is nearly a decade, and that other non-peer-reviewed literature is used nearly as often as formal publications in patent citations (Anderson and Breitzman, 2017; Popp, 2016a,b). The channels from knowledge production to invention are diverse. Nonetheless, these bibliometrics do offer one window into the scientific and invention outputs of ARPA-E projects that buttress the case for the agency's effectiveness in selecting and managing projects that result in scientific achievement. Intuitively, it is understandable that ARPA-E awards, which tend to support earlier-stage research, would produce more publications than EERE awards. However, the results of comparing the publication output of ARPA-E and Office of Science awards suggest that ARPA-E's portfolio, while targeting more applied technologies that could directly affect the energy landscape, is simultaneously able to expand the boundaries of science.

Patents

As with scientific publications, patents are an imperfect but informative indicator of the technological output of federally funded research. As with scientific publications, it is possible to compare the patenting activities of projects funded by ARPA-E with those of projects funded by the Office of Science and EERE, once again controlling for such factors as the size and duration of the research grant and how much time had elapsed since the beginning of the project period.

During the time period investigated, ARPA-E's portfolio of projects resulted in more patents per project than the portfolios of either the Office of Science or EERE. The 13 percent of ARPA-E awards that have resulted in at least one patent compares with 2 percent for Office of Science projects and 5 percent for EERE projects. Moreover, the odds of an ARPA-E awardee being granted at least one patent are three times higher than those for an EERE awardee.

Looking beyond the likelihood of patenting, individual ARPA-E projects also have a higher incidence ratio for patenting than either the Office of Science or EERE over the time period analyzed, suggesting that ARPA-E awardees produce patents in greater numbers than awardees of both of these other offices. Together, the increased likelihood of patenting and the higher incidence rate ratio result in a superior patenting efficiency relative to funds allocated: ARPA-E

[3]For this analysis, a top journal refers to one of the 40 journals from the Thompson Reuters Energy and Fuels category with the highest number of citations for the time period 2005–2015.

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projects returned a patent for each $8.2 million awarded, while the equivalent figures for the Office of Science and EERE were $18.1 million and $28.4 million, respectively.

Goldstein (2016) measured patent quality with two indicators: the first captured whether the patent was cited by other patents and the second the number of claims made on a specific patent. With regard to the first of these indicators, ARPA-E projects had a greater likelihood than EERE projects of producing patents that would be cited. With regard to the second, ARPA-E projects produced patents with more claims relative to the projects of both the Office of Science and EERE. These measures suggest that on average, the patent portfolio of ARPA-E projects is of higher quality than those of the other two officers.

These results reflect favorably on ARPA-E's portfolio. Intuitively, as an applied research program, ARPA-E would be expected to fund projects leading to patents more frequently than the Office of Science, which focuses on basic scientific research. However, the relative patenting performance of ARPA-E and EERE supports ARPA-E's value proposition. Effectively, ARPA-E's research portfolio yields a higher return with respect to inventive metrics.

Publications, Patents, Follow-on Funding, and Firm Formation among ARPA-E Projects

Goldstein (2016) also considered factors that could explain the variance in outcomes among ARPA-E projects themselves. These factors include funding amount, project length, organization type, program, and team composition. The author evaluated this award-level variance with respect both to patents and publications and to additional metrics related to market engagement. Specifically, in addition to patents and publications, Goldstein leveraged ARPA-E's publication of a series of market engagement metrics focused on three types of activity—follow-on public funding, follow-on private funding, and new firm formation.

Overall, there is evidence that market engagement metrics are particularly sensitive to organization type. On the one hand, each of the 20 companies that formed following ARPA-E funding originated in a university. On the other hand, 64 percent of awards that received follow-on private capital were start-up companies, and 77 percent of the awards that received follow-on public funding were in the private sector.

With regard to publications, university projects were more productive than projects of the other organization types. This is intuitively a result of the incentives to publish within academia. With regard to patents, however, the data are unclear. At this stage, patents remain a lagging indicator for ARPA-E's success. The mean time to patent for ARPA-E projects is 4 years, but as discussed earlier, 4 years has not elapsed since the inception of most ARPA-E projects. Given this lag, the committee recognizes that published patent applications could be used as an alternative metric. However, it considers issued patents to be the better long-term metric.

The data suggest that established firms, that is, private-sector companies that were founded prior to 5 years before receipt of an ARPA-E award, were less productive than the other organization types. Specifically, established firms produced fewer patents and publications and received less private or public follow-on funding. However, it is unlikely that these output metrics adequately capture success within a large company. Incentives to publish at an established firm are low relative to those at universities, where publications lead to career advancement, or at start-up firms, where publications serve as technology validation in the market for capital. Established firms also have a broader tool set for protecting intellectual property, such as trade secrets, a resource that can reduce the incentive to patent. Moreover, these firms may not pursue patents on technologies they do not intend to commercialize. Finally, established firms typically finance commercialization without the support of venture capital.

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While established firms may not perform as well as other organization types with respect to these metrics, then, more research is needed to identify an appropriate set of outcome metrics for evaluating ARPA-E projects of established companies.

Team composition appears to have an effect on project outcomes. Applicants to ARPA-E are able to partner with other organizations and divide tasks within the statement of work. Overall, these partnerships appear to have a positive effect, significantly increasing the likelihood that an award will produce a publication or patent or receive follow-on funding. The mechanism for this advantage is unclear. It may be that combining the strengths of multiple organizations contributes to a project's technical progress. But it may also be that partnerships serve as applicant validation, such that technically superior projects are able to attract partners.

Significant variation in project outcomes can be seen across ARPA-E programs. More than 80 percent of projects within the Innovative Materials and Processes for Advanced Carbon Capture Technologies (IMPACCT) and Electrofuels programs have resulted in a publication. Most programs have yet to produce a patent, but 60 percent of projects in the Batteries for Electrical Energy Storage in Transportation (BEEST) program and more than one-third of projects in the OPEN 2009 program have produced patents. The latter figure is particularly striking, as the OPEN programs fund a large number of projects across different technology areas. Projects within two programs—BEEST and Grid-scale Rampable Intermittent Dispatchable Storage (GRIDS)—emerge as highly productive with respect to accelerating commercialization of the funded technology through company formation or follow-on funding. Finally, 100 percent of projects within IMPACCT and GRIDS have received some validation of success through either a patent, a publication, or some form of market engagement.

Summary of External Metrics Analysis

ARPA-E projects produce patents more than projects of either the Office of Science or EERE, with a corresponding reduction in the overall cost per patent. ARPA-E projects also publish more than those of EERE and on par with those of the Office of Science. Relative to EERE, ARPA-E's focus on emerging technology results in an increase in inventive capacity. Relative to the Office of Science, ARPA-E's focus on technology with an applied orientation results in an increase in inventive capacity without diminishing its ability to produce high-quality scientific research. Box 4-2 provides a summary of these observations, which suggest that among these three organizations, ARPA-E is serving a unique role in terms of funding projects that are focused on the energy system, hold both scientific and technological potential, and are associated with early-stage indicators of practical impact. While the committee emphasizes the caveats discussed earlier—that these organizations have different missions and that the metrics used in this analysis represent only intermediate outcomes—these results demonstrate ARPA-E's productivity and the contribution the agency makes to the DOE mission.

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BOX 4-2
Summary of External Metrics Analysis

Publications

- ARPA-E awardees have published at a higher rate than EERE awardees and at a rate similar to that of Office of Science awardees.
- ARPA-E awardees have produced more energy journal publications than Office of Science awardees.
- ARPA-E awardees have produced more top journal publications and highly cited publications than EERE awardees.
- University awardees have published more than awardees from other organization types.
- Standout programs for publications are Electrofuels and IMPACCT.

Patents

- ARPA-E awardees have produced patents at a higher rate than both EERE and Office of Science awardees.
- ARPA-E awardees have generated more cited patents than both EERE and Office of Science awardees.
- ARPA-E awardees of all organization and partnership types have patented at comparable rates, with longer projects producing fewer patents, and higher project funding amounts are associated with the production of more patents.
- The standout program for patents is BEEST.

Market Engagement

- Start-ups funded by ARPA-E do very well garnering private investment.
- Standout programs for attracting market engagement are BEEST and GRIDS.

EVIDENCE OF IMPACT FROM CASE STUDIES

Case studies are one of the methods used by the committee to understand, describe, and then, leveraging the technical expertise of its members, evaluate ARPA-E's operations and impacts (Appendix C contains the full write-ups of the case studies). The descriptions of the selected projects and programs in this section and Appendix C focus on the role played by ARPA-E in their management and the committee's assessment of the potential transformational nature of the respective technologies, the impact on the field, and the expectations for market adoption. An important caveat to this discussion is that these case studies are not intended to be representative of all ARPA-E programs and projects. Together, however, the quantitative analysis of outcomes presented in the previous section and the case studies presented here provide evidence of the current operations, outcomes, and potential long-term impacts of ARPA-E programs and projects on energy sector technologies.

Three types of case studies were conducted: the first focuses on one program, Strategies for Wide-bandgap, Inexpensive Transistors for Controlling High-Efficiency Systems (SWITCHES); the second examines a portfolio of electricity storage (primarily electric battery) projects; and the third includes 10 individual projects grouped into three categories—successful, cancelled, and other. The first two types allowed the committee to understand the implementation and impacts

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of a broad set of projects within both a single program (SWITCHES) and a broad set of programs that funded electricity storage projects. In both instances, the committee aimed to select cases with a broad set of potential impacts. The case studies of individual projects considered their technical potential as well as the role played by ARPA-E.

An important consideration when attempting to assess the success of the programs and projects described in the case studies was the issue noted throughout this report: the state of maturity of ARPA-E. Because most projects are funded for approximately 3 years, there was at most 3 years of data available on completed projects for use in this assessment. Therefore, the focus was on evaluating ARPA-E's operations and providing a technical assessment of whether the selected programs and projects dealt with potentially transformational technologies and/or filled white spaces not being pursued by other public and private entities because of technical and financial uncertainty.

Overview of One Program (SWITCHES)

The committee undertook a case study of a single focused program to understand the implementation of and impacts from a broad set of projects. The committee selected the SWITCHES program because it sees the development of wide-bandgap materials for semiconductors as a potentially transformational development in power electronics. The description of the SWITCHES program in Appendix C highlights many of the hallmarks of ARPA-E, including program director autonomy; investments in high-risk technology; and plans for ensuring commercialization pathways, including the need to keep power electronics manufacturing in the United States.

Program Summary

Power electronics are ubiquitous, and enormous effort is expended on making electronic switching work better. Doing so means developing devices that are more efficient, longer-lasting, lower-cost, and useful in new applications. Improvements in power electronics, for example, can make the grid more efficient and reliable and improve the integration of renewables. There may be other applications as well, including for electric vehicles and lighting. The SWITCHES program solicited proposals for investigation of less well-understood materials with the potential to be tens or hundreds of times better for some vital applications, but not being pursued because the risks of failure were too high and times to market were too long to make such projects competitive for typical industrial research or even much government research funding. Specifically, the SWITCHES program has funded projects pursuing transformational advances in wide-bandgap (WBG) materials, device fabrication, and device architectures to enable the development of new types of semiconductors.

Program Objectives and Impacts

Within the SWITCHES program, ARPA-E recognized the substantial potential for WBG semiconductor materials to yield energy savings and new designs for these applications relative to existing technologies. The goal of this program is to enable the development of high-voltage (approximately 200–2,000 V), high-current power semiconductor devices and circuits that, upon ultimately reaching scale, could offer affordable breakthrough performance in terms of higher efficiencies, higher switching frequencies (and therefore smaller packages), and higher-

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temperature operation (ARPA-E, 2013b). Currently, industrial power electronics circuits are overwhelmingly (>95 percent) built with transistors made out of silicon. Silicon power transistors, however, become increasingly inefficient beyond operating voltages of 400–500 V. There is demand today for power transistors that operate in the approximately 650 V range for circuits that can be plugged into the wall. A second set of needs is in the 1.2–1.7 kV range for automotive applications. The adoption of WBG semiconductors is a move toward higher-frequency circuits, which would allow decreased component sizes and increased efficiencies. Figure 4-3 shows the improvements (lower losses, higher breakdown voltages, and higher-power applications) afforded by various WBG semiconductors over conventional silicon. The left panel of the figure shows the potential for WBG semiconductors to be used in high-power applications with high breakdown voltage. The right panel shows materials with better power device performance (high breakdown voltage and low loss) toward the upper-right corner.

The objective of this program is not only to reduce the barriers to ubiquitous deployment of low-loss WBG power semiconductors, but also to develop approaches that will bring the costs of these devices to functional cost parity with silicon transistors while offering better performance. The program encompasses four major tasks: (1) creating crack-free device substrates using an economically promising method, (2) growing a doped semiconductor layer on these substrates with necessary electronic properties, (3) demonstrating working electronic devices with increasing levels of voltage capability using these new materials, and (4) completing a technology-to-market (T2M) plan. ARPA-E also considers the SWITCHES program a complement to the New Generation Power Electronics Innovation Institute, which is working to help create and manufacture WBG semiconductor-based power electronics in the United States (ARPA-E, 2014b). Within the program, ARPA-E has funded 14 projects: 2 on diamond, 1 on silicon carbide (SiC), and 11 on gallium nitride (GaN). Roughly half of these projects have focused on transistor technology and design and roughly half on the synthesis of better substrate materials on which to build the transistor technology. This is a good mix that underscores the importance of materials issues in the technology.

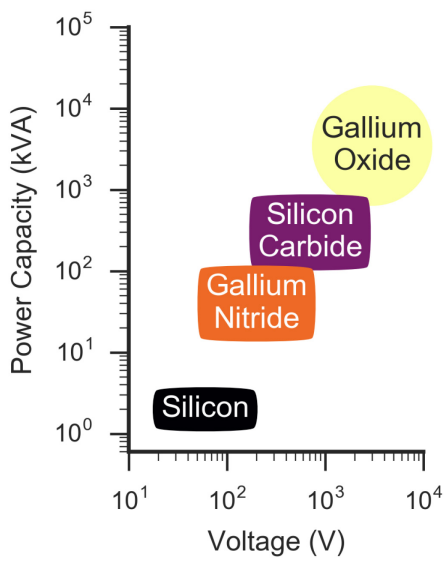

FIGURE 4-3 Relationship between performance dimensions of power capacity and voltage for representative semiconductors and gallium oxide (Ga_2O_3).
SOURCE: NICT, 2012.

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Committee Assessment

The SWITCHES program clearly aspires to have a transformational impact on power semiconductor devices. The design space changes if the boundaries on switching frequency, voltage, and temperature can be significantly moved. However, the risk associated with launching a new materials set for power electronics is high. The default choice is always silicon because it is cheap and has established supply chains. The risk is that the WBG devices could require a decade from invention to profit, let alone broad application, and the tooling is enormously costly—thus the motivation for ARPA-E to develop the SWITCHES program.

The committee's assessment is that the overall project selection within the SWITCHES program has been good in terms of mixing materials, devices, and university and industry skills. However, the lack of participation of most of the major industry players (with the possible exception of Triquint) is significant. It represents a lack of suitable "catchers," companies that are able to manufacturer the technology should it be successful, and thus a risk profile that may be somewhat extreme and the possible need for a refined technology-to-market (T2M) strategy specific to semiconductor technology.

In terms of ARPA-E's role, the performers for these projects demonstrate that Tim Heidel, program director for SWITCHES, and his team have productively and efficiently scoped, shaped, and supported their projects. In general, the committee observed that the program director and core staff are highly competent, dedicated, and responsive. Each project is subject to 10 or more "touches" annually by the program director and the staff front office team, including quarterly reviews, annual reviews, teleconferences, site visits, and other events. "Pivots," or changes in milestones, are rigorously documented and tracked. Further, ARPA-E has not hesitated to cut projects when doing so made sense—2 of the 14 SWITCHES projects were cancelled within 2 years. These actions serve as evidence of the robust and active program management and oversight policies ingrained in ARPA-E's culture.

Overall, the move to low-loss WBG power semiconductor devices would enhance the efficiency of electric motors through improvements to variable-frequency drives; substantially reduce the weight and additional cost of power electronic systems for plug-in electric vehicles; and reduce the cost, weight, volume, and losses from wind and solar electric power inverters. There may be other potential applications as well, although this outcome is not preordained. Engineers do not wait for innovations from the science world before designing things. The corollary is that once scientific discoveries are brought into the design space, engineers will find applications not fully conceived of before. Thus, ARPA-E's efforts in the SWITCHES program are consistent with its goal of bringing potential transformational technologies beyond discovery to the demonstration phase.

Overview of One Portfolio (Electricity Storage)

The committee decided to focus on electricity storage for its portfolio analysis because these technologies constitute the largest fraction—10–15 percent—of ARPA-E's funded projects, making this one of the largest classes of technologies funded by the agency over the past 7 years. The committee performed an overarching high-level assessment of this portfolio to examine, at least for this field, the extent of ARPA-E's impact and whether any broad trends within this group of projects may reflect the strengths and weaknesses of the approaches used by the agency. However, the degree to which this collection of projects can be thought of as a true portfolio is unknown—specifically, when selecting projects for an award, how much consideration is given

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to prior energy storage funding decisions and technical content in the application when weighing the relative programmatic merits of new proposals, especially for those projects awarded in the agency's open calls.

The specific purpose of this exercise was to examine numerically all of the projects addressing electric energy storage that ARPA-E funded from its inception through June 2015. The goals were to

- provide analysis to show how a single class of technologies—energy storage—functioned within ARPA-E;
- search for patterns or trends;
- examine whether the narrative ARPA-E portrays is reflected in reality;
- compare data for this group of projects against the quantitative analyses applied to all ARPA-E projects; and
- provide the other committee subgroups with additional data.

Note that for this analysis, the committee examined only projects focused on storage of electricity. The committee did not consider projects focused on thermal storage or on improvements to battery management systems, sensors, or testing.

Program Descriptions

ARPA-E has funded its electricity storage projects through three focused programs (BEEST, GRIDS, and Robust Affordable Next Generation Energy storage systems [RANGE]), as well as through its OPEN 2009, OPEN 2012, and OPEN 2015 solicitations. The projects in the GRIDS program, which began in 2010, focused on developing technologies that can store renewable energy for use at any location on the grid at an investment cost below $100 per kilowatt hour (kWh). The majority of these projects are electric battery projects, with a few looking at compressed air and flywheel storage approaches. The projects in the BEEST program, which began in 2011, focused on developing a variety of rechargeable battery technologies for plug-in electric vehicles that would meet or beat the price and performance of gasoline-powered cars. The program considered radical improvement of current lithium-ion technologies and new designs using other battery chemistries that incorporate magnesium, sodium, zinc, lithium-sulfur, and lithium-air designs. The projects in the RANGE program, which began in 2013, continued efforts on rechargeable battery technologies for plug-in electric vehicles, focusing on battery designs that would enhance safety, maximize the overall energy stored in a vehicle, and minimize manufacturing costs. The OPEN 2009, OPEN 2012, and OPEN 2015 solicitations were designed to fund transformational breakthroughs across the entire spectrum of energy technologies, including stationary and transportation electricity storage projects. Although a number of storage projects were funded as a result of the OPEN 2015 call, these are very new projects that are not included in the analysis provided below.

Overview of Electricity Storage Portfolio

The committee assessed the electricity storage technology portfolio as part of its overall assessment of ARPA-E's impact and to determine whether any broad trends within these projects might reflect the strengths and weaknesses of the agency's approaches. The vast majority of these projects focused on electric battery technologies. Additionally, the committee did not

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consider programs or projects designed to explore improvements to battery management systems, sensors, or testing. Even with the analysis limited to energy, the important unknown remains of the extent to which ARPA-E considers prior electricity storage funding decisions and technical content in weighing the relative merits of new programs or projects focused on storage, particularly projects awarded through the OPEN solicitations. Thus, it is not possible to know the extent to which this collection of programs and projects can be thought of as a true "portfolio."

ARPA-E has funded 63 electricity storage projects; 5 have been cancelled, 30 are still active, and 28 have been completed. ARPA-E funds were distributed approximately equally among the five programs examined for this analysis that sponsored electricity storage technology—RANGE, BEEST, GRIDS, and the 2009 and 2012 OPEN calls—although the programs that funded more individual projects, in particular RANGE, had lower per-project funding. The typical storage project lasted 2.7 years and consumed roughly $980,000 per year of ARPA-E funding, although both funding levels and durations varied significantly. For example, the longest project stretched over 6 years, and one project received more than $10 million in funds.

Focus Area and Project Type

From a technology maturity perspective, the electricity storage projects were divided between proof-of-concept (36 projects) and prototyping (27 projects), and between stationary (25 projects) and transportation (21 projects) applications. A healthy fraction of the projects (17 projects) were "crossover" in nature in that the technology, if successful, was aimed at both the stationary and transportation markets. Importantly, no project focused on scaling the production level of materials or devices, which intuitively makes sense given ARPA-E's emphasis on early-stage R&D and device proof-of-concept.

The committee reviewed the project descriptions and classified the projects based on their technical focus (Figure 4-4). A number of projects focused on a single technical outcome, such as safety or durability. Five projects had a dual focus on durability and performance. More than half of the projects had a shared focus on cost and performance, while four had a shared focus on cost and durability, and six had cost as their singular focus.

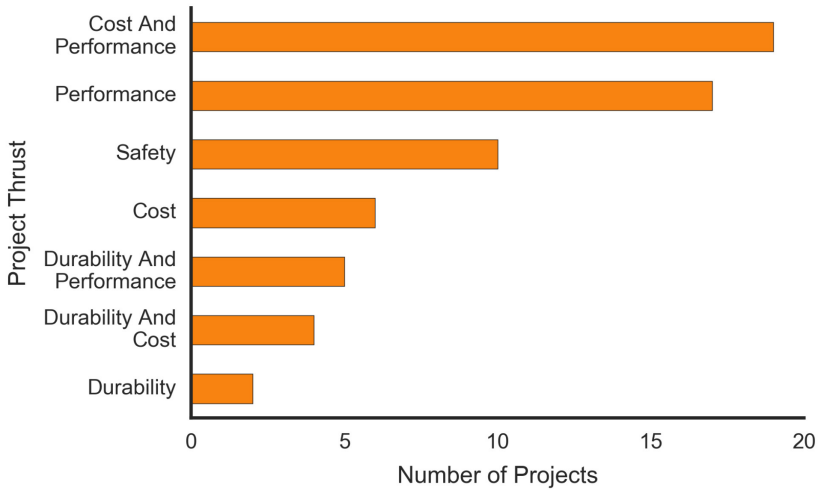

FIGURE 4-4 Focus of ARPA-E electricity storage projects funded from 2009 to 2014.

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Funding of White Space and Project Storyline

As discussed previously, ARPA-E has been mandated to seek out and fund transformational ideas and to find technical white space in which no significant work has been done. In about half of the projects, there is clear evidence of such white space being addressed (Figure 4-5). Further, while there is evidence of significant prior work in the public domain for 50 of the 63 projects, in 25 of these the prior work was done at the institution of the project's principal investigator. These findings show that ARPA-E uses its funding to move early-stage innovations to the demonstration stage.

The committee also looked at the storyline of the projects, meaning the combination of the type of project lead and type of project. The majority of the projects (47 of 63) fall into the category of either a small-company principal investigator further developing a novel technology initiated by that individual or a university professor principal investigator gaining support for a new idea. Additionally, 6 awards went to large companies exploring new concepts.

Metrics of Outputs and Outcomes of Electricity Storage Projects and Comparison with Overall ARPA-E Projects

The committee compiled the metrics of publications, patents, follow-on funding, and commercialized products for ARPA-E's electricity storage projects. These projects had generated a total of 115 peer-reviewed papers and 22 patents as of January 2016. Among the papers, 37 were published in high-impact journals, and 5 were highly cited. A total of 20 projects (approximately 30 percent) received follow-on funding from public or private entities or both. As of the end of 2016, four companies had a mass-manufactured product on the market that had been developed during or after receipt of ARPA-E funding (although in these cases, it is not altogether clear that the product on the market was the same as that which was developed with ARPA-E support).

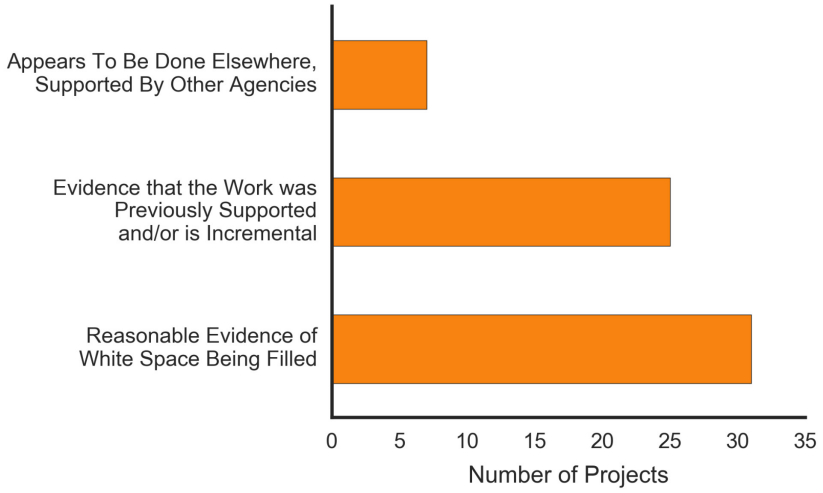

FIGURE 4-5 Degree of novelty and prior support for ARPA-E electricity storage projects.

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The committee also looked at how the outcomes from the electricity storage portfolio compared with those of the entire collection of projects funded by ARPA-E. Company formation has resulted from 7.5 percent of the 475 projects overall, compared with 9.5 percent of the electricity storage projects (6 of 63); the corresponding percentages for follow-on funding are 9.5 percent and 19 percent. Thus it appears that the electricity storage portfolio has funding and technical development outcomes similar to or better than those of ARPA-E projects overall.

Committee Assessment

The committee observed that ARPA-E has funded a wide array of projects related to electricity storage, and that these projects generally do not overlap significantly with projects funded by other sources. Demonstration-style projects require prior work as a base, so it is no surprise that for just over half of the projects, there is evidence of prior similar work having been conducted at either the principal investigator's or some other institution (Figure 4-5). Combined with programs not included in this analysis that focus on thermal storage technologies (High Energy Advanced Thermal Storage [HEATS]), technologies for improving battery management and sensor systems (Advanced Management and Protection of Energy storage Devices [AMPED]), and approaches for testing and evaluating battery storage systems (Cycling Hardware to Analyze and Ready Grid-scale Electricity Storage [CHARGES]), ARPA-E has invested a significant fraction of its resources in improving electricity storage systems. This is a worthy investment given the critical need for improved electricity storage in both the transportation and electricity sectors. The committee considers much of the electricity storage portfolio to have a medium or high degree of technical risk, meaning that its projects have goals that go beyond current technical capabilities and are in many cases difficult to achieve. Further, the committee notes that the technical background of the program directors has been appropriate for most projects, with most having had significant entrepreneurial experience.

Given the high-risk/high-payoff approach both DARPA and ARPA-E take in creating programs and funding projects, the degree of follow-on support resulting from company founding appears to be reasonable for these projects, a significant portion of which found support after the ARPA-E funding ended. On the other hand, it can also be said that the majority of companies involved in ARPA-E electricity storage projects that have actual electricity storage product offerings on the market today were funded by ARPA-E after being founded, and in most cases had a well-defined technical path/plan forward. In these cases, the most common scenario is that ARPA-E funded demonstration projects or product improvements. These types of cases tend to make up the bulk of the projects ARPA-E currently counts as successes, which is not surprising given that it takes 7 to 10 years to mature a new concept that would not have existed substantially prior to being funded. Thus it is quite possible that more of those projects that have received follow-on funding will yield product offerings in the next 5 years.

Individual Projects

Individual projects for case studies can be chosen using three approaches—convenience, purposive, and probability (Morra and Friedlander, n.d.). The committee used a purposive approach for these case studies to ensure that particular phenomena would be represented (Balbach, 1999). The purposive criterion was to select an approximately equal number of projects funded through open and focused solicitations that represented a mix of organizational types, including academia, national laboratories, and companies of varying sizes.

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Applying this criterion, the Case Study Team reached out to several performers (recipients of ARPA-E awards) with the goal of obtaining a specific number of case studies across three broad categories of projects defined by their current status (see Table 4-1):

- "Successes" are projects that the committee or the agency considers likely to have or that have had market success in the energy sector and that have received follow-on private-sector funding.
- "Cancelled" are projects that were ended before the original end date because they were not meeting their goals and appeared likely not to do so eventually.
- "Other" are projects that were completed and that to date have resulted in little or no direct energy market success, but still advanced the state of knowledge.

TABLE 4-1 ARPA-E Individual Project Case Studies

Company Name	Short Project Title	OPEN/Focused	Company Type
Successes—projects that the committee or the agency considers likely to have or that have had market success in the energy sector and that have received follow-on funding			
1366 Technologies	Cost-Effective Silicon Wafers for Solar Cells	OPEN 2009	Small Co.
Foro Energy	Laser-Mechanical Drilling for Geothermal Energy	OPEN 2009	Small Co.
24M	Semi-Solid Flowable Battery Electrodes	BEEST	Small Co.
Harvard University	Slippery Liquid-Infused Porous Surfaces (SLIPS)	OPEN 2012	Univ.
Smart Wires	Distributed Power Flow Control	GENI	Small Co.
Cancelled—projects that were ended before the original end date because they were not meeting their goals and appeared likely not to do so eventually			
General Electric	Nanostructured Scalable Thick-Film Magnetics	ADEPT	Large Co.
Other—projects that were completed and that to date have resulted in little or no direct energy market success, but still advanced the state of knowledge			
Agrivida	Engineering Enzymes in Energy Crops	OPEN 2009	Small Co.
Ceres, Inc.	Improving Biomass Yields	OPEN 2009	Small Co.
HRL Laboratories	Low-Cost Gallium Nitride Vertical Transistor	SWITCHES	Small Co.
Stanford University	Radiative Coolers for Rooftops and Cars	OPEN 2012	Univ.

NOTES: The full case studies are in Appendix C. ADEPT = Agile Delivery of Electrical Power Technology; BEEST = Batteries for Electrical Energy Storage in Transportation; GENI = Green Electricity Network Integration; SWITCHES = Strategies for Wide-bandgap, Inexpensive Transistors for Controlling High-Efficiency Systems.

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ARPA-E performers (principal investigators) for these individual case studies were asked about the state of their research before applying to ARPA-E, their reason for responding to the agency's Funding Opportunity Announcement (FOA), their interactions with their program director and T2M team, the tracking of progress against the metrics established for their project, what they accomplished during the project, and other observations about their project that they wished to share. The case studies also include an assessment of the technology developed during the project and its potential to have an impact in the energy sector.

Short summaries of 3 of the 5 projects that the committee categorized as successful are presented below. (The complete case studies for all 10 projects reviewed are presented in Appendix C.) It should be noted at the outset that, although these projects are categorized as successful in that they show potential for success, none of them have as yet been transformational in the energy sector—as would be expected given the extended period of time in the market required for transformational technologies to become apparent.

Cost-Effective Silicon Wafers for Solar Cells

1366 Technologies is developing a potentially disruptive solar technology, a process aimed at reducing the cost of solar wafer manufacturing by 50 percent by 2020. Silicon solar wafers are the building blocks of solar cells and panels, and reducing their costs has implications for solar's adoption rate. Instead of growing expensive crystals and cutting them into thin fragile wafers, 1366 Technologies casts the wafers directly from molten silicon and can make shapes that are more durable and use less material. The efficiency of these cells compares favorably with that of today's advanced technologies, so 1366's wafers could seamlessly replace wafers currently used in the market while at the same time greatly reducing their costs. Since most solar panels are made outside of the United States, moreover, 1366's technology has the potential to dramatically increase domestic production, thus increasing the nation's energy security (ARPA-E, 2009).

1366 Technologies was selected in the OPEN 2009 solicitation and is the only funded project to develop novel silicon production technologies. At the time of the solicitation, it was a young company in the midst of a funding round and growth (Figure 4-6). ARPA-E funding represents a small fraction of the total capital raised by the company to date, but represented approximately 20 percent of the total raised at the time of the grant. ARPA-E provided 1366 with funding that allowed the company to investigate the basic science that helped lead to a technology capable of being commercialized. This technology ultimately replaced the leading technology options that had received venture capital funding. This project is an example of a case in which a focus on the technology and the freedom to pursue basic science made a promising innovation ready for the market. 1366 Technologies also benefited from the positive press associated with videos and the company's presence at the ARPA-E Energy Innovation Summits.

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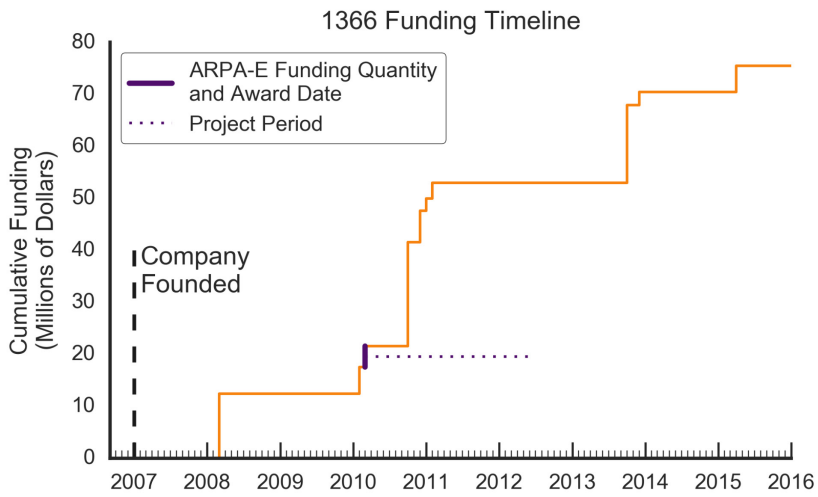

FIGURE 4-6 Funding history for 1366 Technologies.
NOTES: The figure shows the timing and amounts of funding for the company's inception, for ARPA-E funding (purple), and for external funding from other sources (orange). 1366 Technologies received venture capital funding prior to ARPA-E funding; it received $4 million from March 1, 2010, to June 30, 2012; and it received more than $50 million of follow-on funding.
SOURCES: crunchbase.com, 1366tech.com, arpa-e.energy.gov, ARPA-E.

Slippery Liquid-Infused Porous Surfaces (SLIPS)

Harvard University developed various slippery surface technologies intended to enable materials and coatings to achieve extreme energy savings in many industrial settings. The idea for SLIPS was inspired by the slippery surface of the carnivorous pitcher plant, which uses liquid and a mechanical trap to catch insects. By copying the plant's systems, the Harvard team developed a porous material that could hold liquid similarly to the way a sponge holds water. ARPA-E guided the team to investigate commercial applications for the technology and select those with the greatest promise. After a 6-month exploratory effort, the team, together with ARPA-E, chose to develop a SLIPS coating for refrigeration coils that would reduce defrost cycles by enabling faster shedding of frost and water from the surface of the coils. The team tested large-scale coated coils at LG and other local coil-producing companies to demonstrate significant energy savings with SLIPS-coated coils. After 2 years, sufficient proof-of-concept had been established to prompt the launch of a start-up company, SLIPS Technologies, Inc. (STI), to broadly commercialize the technology. STI was launched in October 2014 with venture capital financing led by the venture capital arm of BASF (Figure 4-7). Following this spinoff, ARPA-E extended funding for a third year to enable exploration of the use of SLIPS coatings to prevent marine fouling on ship hulls so as to reduce drag and improve fuel efficiency in various marine applications. Early results demonstrate the technology's potential to address unmet needs in that market with a nontoxic alternative to current antifouling coatings (ARPA-E, 2012).

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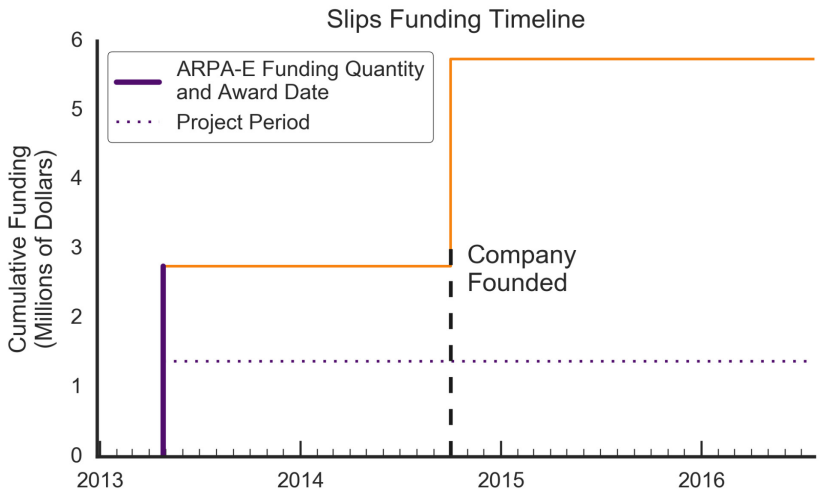

FIGURE 4-7 Funding history for SLIPS.
NOTES: Harvard University received an ARPA-E award of $2.750 million as part of the 2012 OPEN Funding Opportunity Announcement. The project term was from April 26, 2013, to July 25, 2016. A year and a half into the project, BASF Venture Capital raised $3 million in the initial financing round in October 2014 to create a start-up company, SLIPS Technologies, Inc.
SOURCES: crunchbase.com, arpa-e.energy.gov, links from slipstechnologies.com/news, including betaboston.com.

ARPA-E's flexibility and ability to adjust project goals and metrics helped the team achieve meaningful technology goals. The principal investigator highlighted ARPA-E's interest in identifying the right technology and markets for the innovation and its insistence on a rigorous due diligence process to identify such markets. Focusing on early market adoption made funding available to continue the research in more complex areas. This was a successful case of ARPA-E helping a principal investigator's team explore commercially relevant applications for an innovative material, establish proof-of-concept, and then transition the effort to a commercialization path via a start-up company.

Distributed Power Flow Control

Modernizing the electrical grid requires the ability to integrate renewable energy sources into the grid and increase controllability to obtain more throughput. ARPA-E funding helped enable Smart Wires to develop a solution for controlling power flow within the electric grid to better manage transmission capacity. Smart Wires' devices clamp onto existing transmission lines and control the flow of power within the lines. The principles behind the devices are modularity with rapid deployment and ease of redeployment on an increasingly unpredictable grid that is being influenced by the growing penetration of distributed energy resources and other technologies. The modularity of the devices is unique and offers several advantages over traditional power flow control solutions, which typically require long lead times, are highly complex, demand significant capital investment, and ultimately represent single points of failure (ARPA-E, 2011).

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ARPA-E's role in the Smart Wires project was to enable the start-up to build prototype devices and deploy and test them in an operating environment (Figure 4-8). The project represented an instance of very late-stage development, with the technology already in existence and ready for field testing. ARPA-E's financial and advisory contributions were invaluable to Smart Wires' success, helping to derisk the technology for follow-on investors and making it easier for the company to raise capital going forward. Smart Wires' management attributes much of the company's success to ARPA-E's engagement. Since receiving the funding from ARPA-E, Smart Wires has undertaken several rounds of successful fundraising, including $30.8 million in 2015 to bring its PowerLine Guardian product to commercial production.

Summary of Evidence from Case Studies

The case studies evaluated by the committee help demonstrate how the agency is fulfilling its mandate to fund transformational technologies or fill white space opportunities. They provide some early indicators of success and demonstrate how the principles behind ARPA-E play out in the management of programs, portfolios of projects, and individual projects. The descriptions in this chapter and Appendix C are for an array of projects, from those supporting the earliest development of a potential technology from a scientific principle (radiative cooling) to technologies that are emerging into commercial products (e.g., cost-effective silicon wafers for solar cells, SLIPS, Smart Wires).

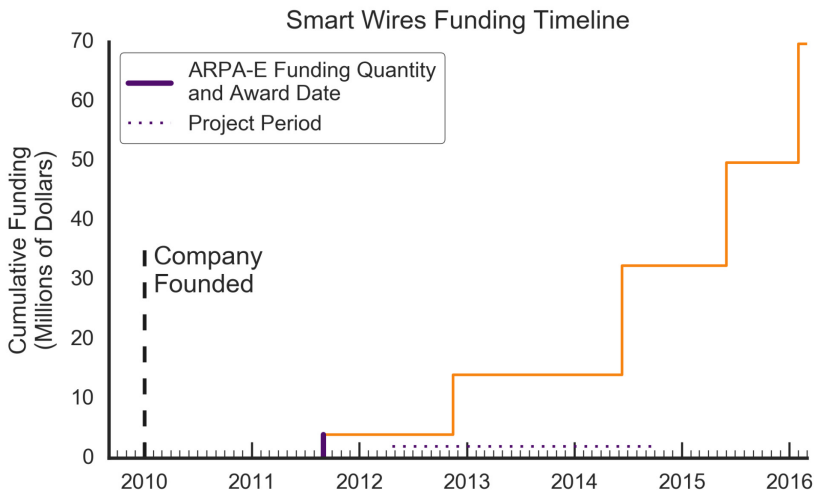

FIGURE 4-8 Funding history for Smart Wires.
NOTES: The figure shows the timing of the company's start-up, the ARPA-E funding (purple), and external funding from other sources (orange) and their amounts. Smart Wires received an ARPA-E award of $3.978 million as part of the GENI (Green Electricity Network Integration) program. The project term was from April 23, 2012, to September 30, 2014.
SOURCES: crunchbase.com, ARPA-E.

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The case studies also illustrate how ARPA-E shapes projects, from providing strategic funding to offering support and guidance for changes in both technological and commercialization pathways. While the summary of the case studies in this chapter focuses on three successful projects, the case study write-ups in Appendix C illustrate other elements of ARPA-E's project selection and management approach. For instance, the Ceres, Inc. project provides an example of a supported firm that moved away from energy markets. Given ARPA-E's goal of spanning boundaries, such outcomes appear more likely for an ARPA-E project than for other DOE programs. Nonetheless, the case also shows how the project manager was able to adapt. In addition, the write-ups in Appendix C emphasize some of the potential issues associated with the high-touch approach of ARPA-E's program directors, including the potential loss of interest in a project when the program director changes and the burdens placed on performers by the number of interactions with the program directors. These findings help support the notion that ARPA-E is implementing the vision Congress had when it authorized the agency. While the committee emphasizes the caveat expressed earlier—that these case studies are not representative of all projects and programs funded by the agency—these findings help demonstrate ARPA-E's productivity and how its unique operations can contribute to its success.

It should be noted that the committee heard presentations from current and former ARPA-E directors and program directors about other projects and programs, including others that could qualify as successes (e.g., Branz, 2015; Gur, 2015; Heidel and Gould, 2015; Majumdar, 2015; McGrath and Umstattd, 2015; Schiff and Zahlar, 2015; Williams, 2015). Time and resources did not allow the committee to undertake a more exhaustive review.

TRANSFORMING ENERGY INDUSTRY ATTITUDES

ARPA-E projects develop technologies for applications in the energy sector, a complex, extensively regulated sector that is capital-intensive and risk-adverse and adopts innovations over long time horizons. ARPA-E is "developing technologies to alter the status quo of the existing energy economy, where much of the end product is a uniform commodity (liquid fuel or delivered electricity)....ARPA-E technologies must enter a crowded market and ultimately compete on price with the legacy fossil and nuclear sectors" (Mehra, 2013). ARPA-E thus operates in a very different competitive landscape from that of DARPA, which has developed completely new technologies in areas in which no prior capability whatsoever existed, such as unmanned aerial vehicles and global positioning technology (Mehra, 2013).

The conservatism of the established energy base provides a critical motivation for the substantial proportion of ARPA-E projects that involve pilot-scale prototyping, demonstration, and testing aimed at persuading risk-averse entities to consider new technological approaches (NRC, 2009). Electric utilities, for example, bulk purchasers of energy technologies from the private sector, have an interest in providing the lowest possible rate for their ratepayers, place a high premium on reliability, and tend to earn a low rate of return on investments. Thus, these entities take a conservative approach to the adoption of new technologies (NASEM, 2016). Similarly, other energy sector companies tend not to adopt next-generation energy technologies unless there is a high rate of return on investment and some degree of assurance that the technology will perform reliably. So despite the promise of ARPA-E technologies, the agency still has the additional challenge of navigating these deployment barriers (Mehra, 2013). Finally, it should be noted that the commercial viability of some ARPA-E projects will depend, at least in

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part, on policies that incorporate environmental costs or impact the relative costs of renewable energy compared with fossil fuel energy.

In such an environment, ARPA-E demonstration projects that result in attitudinal changes in the energy industry may be transformational. Concentrating the agency's programs and projects in white space research areas and on technologies that have high risk and the potential for high reward has a number of benefits apart from avoiding duplication of existing research. It challenges established attitudes and entrenched constituencies and may alter pathways, barriers, and risks in key technology areas, and it builds community knowledge and expertise in new areas as well. Most of the project case studies examined for this study involved prototyping, data gathering in operational environments, scale-up, and the development of pathways to commercialization rather than research into entirely new scientific concepts. As noted in the full Smart Wires write-up in Appendix C, for example, the program director predicted that utility executives' realization that they can modulate power flows on command would have transformational effects on their decision making, ultimately leading to far more efficient, lower-cost transmission.

CREATING NEW COMMUNITIES OF RESEARCHERS

The statement of task for this study directed the committee to assess the success of ARPA-E's focused technology programs in spurring the formation of new communities of researchers in specific fields. ARPA-E's Strategic Vision 2013 states that the agency's focused programs are "developed through engagements with diverse science and technology communities, including some that may have not traditionally been involved in the topic area..." (ARPA-E, 2013c). Project applicants are encouraged to form interdisciplinary teams covering broad ranges of technology. The FOA for the FOCUS program, for example, stated that applicants "may benefit from formation of interdisciplinary teams with expertise in more than one of the following areas: non-imaging optics, advanced optics and photonics, mechanical engineering…." (ARPA-E, 2014c).

The committee finds that it is too soon to assess whether ARPA-E programs will result in the creation of permanent new communities of researchers. The agency is actively seeking to convene diverse constituencies: ARPA-E's workshops, kickoff sessions, and annual program reviews are all institutional mechanisms not only for developing focused programs but also for building communities. These activities could evolve into new, lasting research communities if cultivated over the long term. In his presentation to the committee, former ARPA-E director Arun Majumdar (2015) indicated that the agency does not initiate a program without convening a workshop that not only helps avoid duplication but also "brings people together from different disciplines, and magic happens." Majumdar recalled that with respect to power semiconductors, "dots had to be connected. The soft magnet guys have to talk to the wideband semiconductor guys." Though it may be too early to assess whether ARPA-E programs result in the creation of permanent new research communities, this may be a topic for ARPA-E to assess in a future evaluation.

The DARPA Model for Orchestrating Communities of Scientists

The desire of ARPA-E to foster new communities of researchers in energy follows DARPA's lead in creating such communities. Fuchs (2010) provides a comprehensive study of the operations of DARPA's Microsystems Technology Office between 1992 and 2008 that

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highlights the key role played by that agency's program managers in convening and managing social networks to achieve technological objectives.

According to Fuchs (2010), key to understanding DARPA's role in influencing technology directions is understanding the role of the program manager. The program manager is not just someone who "opens windows" for researchers to bring funding ideas (Block, 2008) or merely acts as a "boundary spanner" or "broker" who connects different communities (Ansell, 2000; Block, 2008), but rather a person who plays a more deliberate role in changing the shape of the network of scientists so as to identify and influence new directions for technology development. Processes used by DARPA program managers for seeding and encouraging new technology trajectories so as to "prevent technological surprise" include

- bringing star scientists together to brainstorm new ideas, whether informally (just three star scientists called together by a program manager) or more formally through such mechanisms as the Information Science and Technology working groups and the Defense Science Board (DSB);
- seeding disparate researchers around common themes;
- encouraging early knowledge sharing among these star researchers through program reviews in which they present their results to each other;
- providing external funding agencies and industry with third-party validation for new technology directions; and
- not sustaining the technology (e.g., ensuring that industry or other funding agencies eventually take over).

Fuchs (2010) concludes that the DARPA program managers become a central node to which information from the larger research community flows because each is a former member of the research community who has risen in status and holds the promise of providing funding. In this role, they do not give way to the invisible hand of markets, nor do they step in with top-down bureaucracy to "pick technology winners." Instead, they are in constant contact with the research community, bringing people together to brainstorm new directions, understanding emerging themes, matching these themes to military needs, "betting on the right people," connecting disconnected communities, positioning competing technologies against one another, and maintaining the birds-eye system-integrating perspective that is critical to integrating disparate activities across the nation's innovation ecosystem.

Finally, throughout these activities—whether bringing together members of research communities that may not normally interact or funding an entire suite of technologies necessary to achieve an integrated outcome—DARPA program managers contribute a system-level perspective to organizing national R&D. DARPA has been able to cultivate such communities over the long term by continuing to fund activities in focused areas until the technology and the community can be sustained outside the walls of the agency. Such accomplishments as the early development of the Internet, Global Positioning Systems, and autonomous vehicles were not the result of a single successful project or program, but of the cultivation of a community across a pyramid of interdependent technologies (Fuchs, 2010) over an extended period of time.

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Examples from ARPA-E

The committee focused on two programs in which ARPA-E is bringing together communities of researchers that have tended not to interact in the past. The committee was unable to identify instances in which ARPA-E programs are attempting to play a longer-term role in their evolution into new, lasting research communities.

Advanced Management and Protection of Energy storage Devices (AMPED)

ARPA-E's AMPED program is an example of a case in which the agency has created a community with longer-term potential. The program was designed to foster advanced sensing, control, and power management systems so as to change conventional attitudes toward battery management. Ilan Gur, a program director who participated in AMPED, said that most advanced battery research had focused on new chemistries, so the AMPED program was devised to use novel modeling, sensing, and control technologies to yield lighter, cheaper batteries, producing nearly as great an impact as new chemistries (Gur, 2015).

Gur (2015), for example, recalled for the committee that ARPA-E talked to people outside the field of battery research in developing information about acoustic monitoring techniques usually associated with geological research but with possible application in monitoring battery performance. The agency kicked off the AMPED program with a 2-day meeting whose participants included not only the project performers, but also representatives from academia, industry, government, and the national laboratories (ARPA-E, 2013d). In March 2015, ARPA-E convened a 3-day annual program review meeting for AMPED whose attendees included project teams and key stakeholders in advanced battery management from academia, industry, and government (ARPA-E, 2015). At the meeting, participants had opportunities to engage in discussions with the AMPED teams on topics that included how to position these new battery management systems for strategic investors (ARPA-E, 2015). Gur (2015) concluded that ARPA-E catalyzed new research in the area of battery management systems that generated excitement in the private sector.

Full-spectrum Optimized Conversion and Utilization of Sunlight (FOCUS)

ARPA-E's FOCUS program is an example of how the agency has convened different research communities that previously existed in separate spheres. The program was aimed at developing new hybrid solar energy converters and hybrid energy storage systems that would accept both heat and electricity from variable solar sources. A subsidiary objective of the program was to form a diverse research community of experts in the concentrating solar power (CSP) and solar photovoltaics (PV) fields that would innovate together through this program (ARPA-E, 2014c). These include CSP mechanical engineers, PV semiconductor materials and device scientists, optics/photonics experts, chemists, low-cost manufacturing experts, and system integrators (ARPA-E, 2014c). CSP and PV are such fundamentally different technologies that Howard Branz, a program director who participated in the program, recalled for the committee that prior to FOCUS, the "PV and solar thermal communities were totally separate, didn't talk to each other" (Branz, 2015).

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ARPA-E Energy Innovation Summit and Kickoff Meetings

In testimony before the committee, several ARPA-E representatives mentioned the agency's annual Energy Innovation Summit in the context of community building. Additionally, the committee attended the kickoff meetings of several projects. The committee observed that these events provide venues for communication, but likely do not themselves indicate creation of a community. There is little evidence that a community would be sustained in the absence of funding, and the events are focused on funded projects, not the creation of new directions. The committee found no evidence of communities spontaneously forming without the direction and influence of ARPA-E program directors, an observation that further reinforces the pivotal role of the program directors within ARPA-E.

IMPROVING PUBLIC AWARENESS OF ARPA-E ACHIEVEMENTS

While the committee noted significant outcomes emerging from projects funded by ARPA-E, these achievements may not be sufficiently appreciated outside of energy research communities within companies, government agencies, and academic institutions. While many exhibitors at the ARPA-E Energy Innovation Summit and participants in program meetings attended by the committee appeared to have the capability to discuss the technical aspects of their projects, the compelling nature of those projects and how they could be transformational often was unclear. The committee is concerned that the inability to deliver compelling messaging consistently in the language of the general public limits ARPA-E's ability to describe its programs and projects to the broader set of policy makers and the public at a time when energy issues often are at the forefront of public debates. The National Science Foundation has long recognized education as a key element of its mission, enabling it to share excitement and inspire the next generation of breakthrough science performers. Such a function may be even more relevant for ARPA-E as the customers of an innovation funded by the agency often are business leaders who lack deep science or engineering knowledge.

It is already difficult to demand that performers simultaneously be experts in their own technical fields, adept in business, and skilled in both project management and government relations while communicating work that crosses traditional boundaries of technical training. The committee notes that ARPA-E has used videos and webinars through the ARPA-E University portion of its website (http://arpa-e.energy.gov/?q=arpa-e-site-page/arpa-e-university) as part of its training efforts, and this might be one avenue for facilitating such communication training for performers. However, expecting these same people to be skilled at explaining technology to a general audience—for example, relating narrow innovations in plasma physics to daily life—is unreasonable. Engaging communications experts would be a valuable way to improve awareness of ARPA-E's achievements and dispel myths about what is essential to U.S. economic and energy security. Such experts could assist in developing the compelling and instructive graphics needed to show the potential role of specific programs in producing transformational breakthroughs. Their efforts could clarify that diverse metrics are necessary to understand the success of individual projects and programs and help dispel the idea that there may be a single metric suitable for evaluating all projects and programs.

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ADDITIONAL METRICS THAT MAY BE USED FOR TECHNOLOGY ASSESSMENTS

As discussed earlier in this chapter, an important part of this study was developing systematic metrics for the social, economic, and environmental impacts of ARPA-E projects, but given the relatively short timeframe since ARPA-E commenced operations, there was little measurable evidence to use for assessing performance against the agency's long-term objectives. Moreover, there are a variety of important outcomes that are difficult to assess including:

- funding critical science that is essential to achieving energy transformation and/or discovering new directions;
- demonstrating the viability of existing scientific theory that is critical to energy transformation;
- demonstrating that particular technological pathways should not be pursued; and
- funding individual components of the energy system that may be underfunded and could hold back advancement throughout the system because of interdependencies with other components, including funding white space technologies, funding white space where other agencies or companies are not working, funding a portfolio of projects to ensure compatibility across the energy system, and funding activities for an existing technology to drive down its costs or the cost-to-performance ratio and enable its deployment to be transformational.

Other metrics that should be considered for a longer term assessment include metrics of commercialization, technological or environmental impacts, lessons learned, and the creation of novel collaborations or new research communities. One metric of success is a product based on the technology that generates revenue. Another metric of commercialization could be revenue from licensing patents if the firm chooses not to manufacture the product itself. (Arora, 1995; Cannady, 2013; Chan, 2014). Given the early stage of development of most projects and their 3-year duration, commercialization would not be an appropriate metric for many projects while they are supported by ARPA-E. Nonetheless, commercial success is one important objective for the technologies supported by ARPA-E and necessary for any technology to transform the marketplace. However, long lags exist between basic and translational research support and commercial outcomes (Popp, 2015).

ARPA-E should also keep track of the lessons learned about what works and what does not work. Knowledge about particular technological pathways that should not be pursued is as important for the advancement of science and technology and successful technologies. These results are often more difficult to publish, if published at all. Finally, the success of ARPA-E's focused technology programs at spurring formation of new communities of researchers in specific fields is another metric to consider in assessing the agency. Studies could be done to evaluate whether research projects funded by ARPA-E are more likely to involve novel (e.g., first-time) collaborators relative to projects funded by other energy agencies or industry (Colatat, 2015). When metrics are not available, case studies can provide qualitative information on project and program outcomes.

ARPA-E has in place an extensive data gathering and recordkeeping system at the project level that can track and monitor internal metrics and facilitate active program management. It has a less extensive system that can collect, track, and report publicly available high-level innovation

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metrics such as publications, funding from other sources, and intellectual property information, including disclosures and patents. Moreover, these traditional innovation metrics are poorly suited to evaluating ARPA-E's activities. What really is needed is a framework that maps the linkages of technical goals of each program through intermediate outcomes, such as traditional innovation metrics, to the agency's statutory mission, means, and goals.

Developing and implementing such a framework for impact evaluation would be very valuable and important for ARPA-E to undertake as soon as practicable, providing the agency greater ability to assess and demonstrate its value and impact. Critically, ARPA-E should not delay implementation. The longer the agency waits, the more difficult it will be to implement such a framework and the less valuable it will be. If too much time is lost, it will become more difficult if not impossible to assess program impacts in a way that allows for meaningful responses to what is learned from utilizing the framework—i.e., by making tweaks to systems or revisions intended to maximize impact (Davis et al., 2008; Link et al., 2012).

The agency could link data from its robust internal database of project-level metrics to program-level goals, including indicators of commercial and noncommercial outcomes over the short and long terms; connect those goals to observable innovation metrics; and then translate those metrics into progress toward achieving the agency-level mission and goals. Such a framework would need to include a system for tracking performers postfunding for at least 10 years, and very likely longer, to capture technologies that are transferred in arms-length transactions along with other ways of observing technology deployment. As of this writing, the agency already has taken steps supportive of creating such an impact assessment framework, such as creating and filling in September 2016 a new staff position of Senior Technical Advisor for Impact and Assessment.

SUMMARY OF FINDINGS AND RECOMMENDATIONS

ARPA-E's Success

Finding 4-1: ARPA-E has funded research that no other funder was supporting at the time. The results of some of these projects have prompted follow-on funding for various technologies, which are now beginning to enter the commercial market.

As a result of ARPA-E's activities, companies have been founded, patents applied for and issued, and papers written about work performed in projects funded by the agency. Dead ends also have been identified, which, if properly documented, would provide important reference data for later researchers. In general, the agency was not solely responsible for the development of these technologies, as most of them originated before ARPA-E funding was forthcoming. In a number of cases, however, ARPA-E provided crucial early-stage funding and frequent technical and market analysis expertise that enabled a company or idea to pass at least partially through the "valley of death,"[4] as ARPA-E was established to do. It is too early to determine conclusively

[4]As noted in "10 Ways for Startups to Survive the Valley of Death," the term "valley of death" is common in the start-up world, referring to the difficulty of covering the negative cash flow in the early stages of a start-up, before its new product or service is bringing in revenue from real customers (Zwilling, 2013).

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whether any technology supported by ARPA-E will be truly transformational; this assessment can be made only retrospectively, after the passage of a decade or more.

Finding 4-2: The projects ARPA-E has funded support its statutory mission and goals.

Measuring and assessing the impact of any one project or program on ARPA-E's statutory mission and goals is very difficult. Having a longer time series of data would be helpful to this end, but would not eliminate the inherent challenges since Congress's goals for the agency are highly diffuse and affected by disparate factors. At this early stage, however, it is still possible to gain some understanding of whether ARPA-E's activities have contributed to supporting the agency's mission and goals. Currently available qualitative and quantitative evidence suggests that ARPA-E has funded projects that support its statutory mission and goals. Several supported technologies have received follow-on private funding and appear to be on a trajectory toward commercialization of products—with at least one already in the marketplace—that will impact the energy sector and the environment. The committee's review of programs and selected projects indicated that the agency created some funding programs for technology areas that the private sector or other federal agencies would have been unlikely to pursue. One example is the program on wide-bandgap, high-voltage solid state electronics. ARPA-E also has funded projects in areas that clearly overlapped with areas supported by the private sector and other funding agencies. In some of those cases, ARPA-E was a key accelerator.

Finding 4-3: While 6 years is not long enough to produce observable evidence of widespread deployment of funded technologies, there are clear indications that ARPA-E is making progress toward its statutory mission and goals.

ARPA-E has provided crucial early-stage funding for some performers. One quarter of these projects have received follow-on funding for continued work on technologies that now are poised to enter the commercial market. Many funded projects have produced publications in peer-reviewed journals, and some have received patents. However, most transformative energy technologies require many years, often several decades, to go from nascent research to first marketable product. ARPA-E projects are funded for roughly 3 years, a far shorter time.

Two important observations can be derived from these facts. First, there is an inherent tension between the pressure to demonstrate success by bringing a product to market quickly and funding of early-stage technologies with the potential to be transformative in the face of the many years of work nearly always required to realize a technology's full impact. Second, after 6 years of operation, there exist fewer than 4 years of projects to serve as evidence of progress toward ARPA-E's mission and goals. These two observations speak both to the need to consider ARPA-E's value in context and over a duration that is well aligned with the agency's mission, and to the need for more and better data for fully understanding that value. Nonetheless, the committee is confident that the evidence obtained and analyzed for this study indicates that ARPA-E has grown from a concept into a functioning organization and has made demonstrable progress toward achieving its mandates.

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Recommendation 4-1: Policy makers should recognize that there is limited evidence to date on transformational impacts emerging from ARPA-E, given the short time since ARPA-E began.

The agency had been in operation for only 6 years when this study was undertaken. By comparison, as noted above, truly transformational technologies emerge over much longer time periods. The committee emphasizes the most fundamental tension to be managed by ARPA-E between having a short-term impact on a technology within the 3-year funding timeframe while producing transformational technologies.

ARPA-E's was expressly created to achieve long-term environmental, security, and competitiveness goals. It was structured to fund and manage R&D undertaken by entities other than the agency rather than undertaking its own R&D activities. Because the agency is tasked with seeking out transformational technological advances, it has necessarily utilized novel operational benchmarks to try to accomplish its goals. Together these findings mean that any assessment of the agency will encounter a well-known problem in R&D management: since sufficient time has not passed for outcomes to have become evident, an assessment cannot draw strong conclusions unless the enterprise is in an extreme situation, such as doing very badly. These same findings also make clear that ARPA-E is not in an extreme situation. The agency is not failing and is not in need of reform. In fact, attempts to reform the agency—such as pressure to show short-term successes rather than focusing on its long-term mission and goals—would pose a significant risk of harming its efforts and chances of achieving its mission and goals.

ARPA-E may eventually be assessable by the impacts on energy and environment of the technologies and products it has enabled, much as the Defense Advanced Research Projects Agency (DARPA) is judged. To gather data on impacts will require patience, however, as many years still must pass before the full impacts of ARPA-E's investments will be known. ARPA-E projects develop technologies for applications in the energy sector, a sector that is generally capital-intensive, risk-adverse, and adopts innovations over long time horizons.

Despite these limitations on an early assessment, currently available qualitative and quantitative data suggest that ARPA-E is pointed in a positive direction—it has funded projects that support its statutory mission and goals—and there are signals that indicate potential for future success. A review of programs and selected projects suggests that the agency has identified technology areas that neither the private sector nor the federal government would likely have pursued alone, funded projects when no other entity would, and provided crucial early-stage funding for some projects. One example is the program on wide-bandgap, high-voltage solid state electronics. In other cases, ARPA-E has accelerated the funding of projects in areas also supported by other public funding and private investors.

Maintaining Focus on Funding High-Risk Technologies and Innovations

Finding 4-4: One of ARPA-E's strengths is its focus on funding high-risk, potentially transformative technologies and overlooked, "off-roadmap" opportunities pursued by neither private firms nor other funding agencies, including other programs and offices within DOE.

This finding describes the importance for ARPA-E of seeking high-risk, potentially transformative technologies and "off-roadmap" opportunities that have been overlooked or ignored by both private firms and other offices and programs at DOE or other funding agencies.

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This makes ARPA-E's focus on potentially high-impact innovations in both cases vital to accomplishing the agency's mission. ARPA-E's underlying organizational features—including encouraging its program directors to seek potentially high-impact projects and recognizing that many of its projects will produce only valuable knowledge, including knowledge of research pathways that should not be further pursued, but not commercialized products—is distinctive within DOE.

Maintaining this focus will be one of the greatest challenges for ARPA-E in the future. It is not guaranteed that ARPA-E will be able to maintain a culture of pursuing high-risk but potentially transformative technologies and research pathways characterized as novel or significantly underexplored as the energy technology landscape evolves. ARPA-E leadership and the secretary of energy should actively work to sustain this culture. ARPA-E should continue to balance its overall portfolio between innovations that appear to have the potential to be transformative and other important opportunities that are being ignored despite their potential for impact.

Recommendation 4-2: The director of ARPA-E should continue to promote and maintain a high-risk culture within the agency. Means to this end include periodic reassessment to ensure that the principles that drive support for high-risk projects are being maintained.

Recommendation 4-3: ARPA-E should continue to use processes designed to identify and support unexplored opportunities that hold promise for resulting in transformational technological advances.

When conducting future evaluations, it is important for ARPA-E and policy makers to remember that the agency is tasked with supporting "high-risk/high-reward" research. This implies a skewed distribution of research outcomes: many projects and even programs may not produce tangible outcomes measured against the agency's overall goals and means, but the overall return of the whole portfolio may be positive because of a few highly successful projects.

Clarification of ARPA-E's Mission

Finding 4-5: Some of the language used by ARPA-E creates an impractical expectation and mission that are not necessarily in the agency's original authorizing statute.

Problematic expectations expressed to the committee included that ARPA-E should be the only federal agency funding a technology and that all projects should be transformational.

Recommendation 4-4: ARPA-E should be careful not to misinterpret or extend its interpretation of its original authorizing statute, whose careful language is appropriate to the agency's mission and goals.

For example, ARPA-E should not be measured by or consider its mission to be serving as the only federal agency funding a technology or funding only transformational technologies. The agency may best be served by a balanced portfolio of projects aimed at attaining both large and

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small successes, not only "home runs." Funding white space can be orthogonal to funding transformational technologies, including "filling in" where other agencies are not working. And driving down costs (or the cost-to-performance ratio) for an existing technology to enable its adoption could be transformational to the energy system.

ARPA-E's success also should not be measured based on whether a funded project has reached the market. Equally important outcomes include (1) funding critical science that is essential to achieving energy transformation and/or opening up new directions, (2) demonstrating the physical viability of existing scientific theory that is critical to energy transformation, (3) demonstrating that particular technological pathways should not be pursued, and (4) funding individual components of the energy system that may be underfunded and, for example, could hold back advancement throughout the system because of interdependencies.

High-Touch Management and Reporting Requirements

Finding 4-6: The high-touch nature of project management at ARPA-E is a hallmark of the agency and has been praised by performers. That said, quarterly reporting in terms of required written documentation is currently challenging, depending on the technical context. Given that quarterly written reports are offset in time with site visits from program directors and their teams, a project performer may end up having 8–10 direct interactions with ARPA-E per year.

Recommendation 4-5: ARPA-E should consider streamlining the quarterly reporting process so it consists of presentations to the program directors and their teams, with only the fourth-quarter/annual report providing full written details. Doing so would allow the agency to maintain close contact with performers while relieving some of the burdens on them.

Documenting Lessons Learned

Finding 4-7: Through its projects and programs, ARPA-E is accumulating not only technical knowledge of what is working and has promise, but also potentially very useful information on what does not work that can be an important addition to ARPA-E documentation.

As a condition of funding, the agency may wish to require that each performer document what does not as well as what does work. Further, ARPA-E should explore publishing an annual, easily referenced lessons learned document focused on what performers learned does not work, for the benefit of the scientific community, to aid in the review of existing programs, and to serve as a reference for future programs. In this last case, ARPA-E may need to consider producing both an internal document with confidential information available only to its program directors and a sanitized public document with no performer-confidential information.

Recommendation 4-6: ARPA-E program directors should compile a document or other repository of lessons learned on all projects, including both positive and negative outcomes.

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Improving Awareness of ARPA-E's Role among the Public and Policy Makers

Finding 4-8: ARPA-E is in many cases successfully enhancing the economic and energy security of the United States by funding transformational activities, white space, and feasibility studies to open up new technological directions and evaluate the technical merit of potential directions. However, ARPA-E is doing a poor job of creating awareness of these very real successes while at the same time holding itself to a metric of success that is not aligned with its authorizing statute or fundamentally essential to the energy and economic security of the United States (see Finding 4-5).

The process of developing an energy technology is a complex story involving many actors and events. Successful energy technologies often have interesting stories with long pathways from basic scientific discoveries and engineering innovations to mainstream products. Those pathways are often complex, convoluted, and unique. Succinct language and visual forms of communication would be quite valuable in making the stories and processes accessible to a range of audiences, especially non-technical ones. For the SWITCHES program, for example, it would be helpful to have a one-page explanation, written for general audiences, relating why this program matters and its potential transformational impact should it prove successful. One way ARPA-E could increase and improve its communication for non-technical audiences would be to engage experts in communication of popular science who could train staff or perhaps help produce materials. Regardless of the story being told, ARPA-E should ensure that key audiences such as Congress, the secretary of energy, and other members of the administration clearly understand the value of ARPA-E's activities.

Recommendation 4-7: ARPA-E should increase and improve its communication for non-technical audiences, including the impact of its activities, the diversity of appropriate metrics to judge the success of individual projects and programs, and the fact that no single metric is appropriate for this purpose.

Improving ARPA-E's Measurement and Assessment of Its Impact

Finding 4-9: ARPA-E is not yet able to assess the full extent to which it has achieved its statutory mission and goals. However, it is in a good position to develop a framework for prospectively mapping data on project selection and management to mission success and goal achievement.

ARPA-E's active project management processes include a an extensive data gathering and recordkeeping system to monitor project status through internal metrics such as progress toward milestone, but does not extensively collect, track, and report publicly available high-level innovation metrics such as publications; funding from other sources; and intellectual property information, including disclosures and patents. The agency is in a good position, though, to create a mapping framework that links the technical goals of each program through intermediate outcomes, such as traditional innovation metrics, to the agency's mission, means, and goals.

The agency could link data from its robust internal database of project-level metrics to program-level goals, including indicators of commercial and noncommercial outcomes over the

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short and long terms; connect those goals to standard, observable innovation metrics; and then translate those metrics into progress toward achieving the agency-level mission and goals. Such a framework would need to include a system for tracking performers for at least 10 years following the end of their funding from ARPA-E, and very likely longer, to capture technologies that are transferred in arms-length transactions along with other ways of observing technology deployment.

It is critical to keep in mind that ARPA-E itself is, and will continue to be, the entity best positioned to establish this framework, what to measure, and how to incorporate the information learned thereby into agency operations and decision making. The agency should not be bound by legislative mandate that specifies methodology or inclusions for any future impact assessments. ARPA-E needs to be allowed to remain nimble so it can respond quickly to new information. ARPA-E already is known for its internal reflection and efforts to improve its operations and outcomes. Designing and implementing such a framework would make the agency an exemplar of public agency self-evaluation and evidence-based improvement. ARPA-E should be emboldened and empowered to develop and implement such a framework in a way that best serves its mission and goals.

Recommendation 4-8: The ARPA-E director and program directors should develop and implement a framework for measuring and assessing the agency's impact in achieving its mission and goals.

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Appendix A

Committee Member Biographies

Pradeep K. Khosla *(Chair)* is chancellor at the University of California (UC), San Diego. He has had an outstanding career as a researcher in the fields of electrical and computer engineering, and possesses critical technical, leadership, and technology commercialization experience that was essential to this study. An internationally renowned electrical and computer engineer with three published books and more than 350 published articles and book chapters, Dr. Khosla previously served as dean of the College of Engineering and Philip and Marsha Dowd University Professor at Carnegie Mellon University, where he spent the majority of his career. From 1994 to 1996, he also served as a Defense Advanced Research Projects Agency (DARPA) program manager in the Software and Intelligent Systems Technology Office, Defense Sciences Office, and Tactical Technology Office. He has direct experience with commercializing technology through spin-offs of his own research into private companies, as well as service on boards for several companies. Dr. Khosla became UC San Diego's eighth chancellor in 2012. At the university, he initiated and led a comprehensive strategic planning process to unify the campus and define the university's future. Dr. Khosla is an elected member of the National Academy of Engineering and the American Society for Engineering Education. He has served on three prior National Academies ad hoc study committees, and served as vice chair of the Charles Stark Draper Prize Committee in 2014. He is a fellow of the Institute of Electrical and Electronics Engineers, the American Society of Mechanical Engineers, the American Association for the Advancement of Science, the American Association of Artificial Intelligence, and the Indian Academy of Engineering. He is an honorary fellow of the Indian Academy of Science.
Dr. Khosla is also the recipient of numerous awards for his leadership, teaching, and research, including the 2012 Light of India Award, a Lifetime Achievement Award from the American Society of Mechanical Engineers, and the George Westinghouse Award for contributions to improve engineering teaching. In 2012, he was named as one of the 50 most influential Indian-Americans by SiliconIndia.

Maxine L. Savitz *(Vice Chair for Technical Evaluation)* has extensive experience in energy technologies and has served on numerous energy-related committees at the National Academies. She also has served on the Charles Stark Draper Prize Committee (chair, vice chair, and member). Dr. Savitz is an elected member of the National Academy of Engineering, where she served as Vice President from 2006-2014. She is the retired general manager for Technology Partnerships at Honeywell, Inc. (formerly AlliedSignal) and previously was the general manager of AlliedSignal Ceramics Components. She was employed at the U.S. Department of Energy

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(DOE) and its predecessor agencies from 1974 to 1983 and served as deputy assistant secretary for conservation. Dr. Savitz currently serves on the board of the American Council for an Energy Efficient Economy and on advisory bodies for Pacific Northwest National Laboratory, Sandia National Laboratories, and Fermi Research Alliance. She served on the Massachusetts Institute of Technology's (MIT) visiting committee for sponsored research activities. In 2009, Dr. Savitz was appointed to the President's Council of Advisors for Science and Technology and served until January 2017. She is a fellow of the California Council on Science and Technology. Past board memberships include the National Science Board, the Secretary of Energy Advisory Board, the Defense Science Board, the Electric Power Research Institute (EPRI), Draper Laboratories, and the Energy Foundation.

Pierre Azoulay is the International Programs Professor of Management at the MIT Sloan School of Management. He is also a research associate at the National Bureau of Economic Research. Dr. Azoulay is an applied economist deeply interested in understanding the forces that shape the rate and direction of scientific and technological progress. Currently, he is studying the career choices of postdoctoral fellows in the life sciences and how they impinge on long-term research productivity, the impact of scientific retractions on the fate of scientific fields and authors embroiled in scandal, and the effects of public investments in biomedical research on the patenting rates of private-sector biopharmaceutical firms. In the past, he has investigated the effects of alternative funding schemes on risk-taking behavior in science and contributed to the public policy debate on reform of the peer review system for the funding of basic research. Dr. Azoulay earned his Ph.D. from MIT in 2001. From 2001 to 2006, he was an assistant professor of management at the Graduate School of Business, Columbia University.

Terry Boston retired in December 2015 after serving eight years as CEO of PJM Interconnection, the largest power grid in North America and the largest electricity market in the world. Mr. Boston is a 2017 U.S. presidential appointee to the National Infrastructure Advisory Council (NIAC/DHS). Starting in 2016, he is on the Board of GridLiance. He has served as president of the Association of Edison Illuminating Companies and past president of GO 15, the association of the world's largest power grid operators. He also served as a U.S. Vice President CIGRE (International Council of Large Electric Systems). Mr. Boston is a founder and past chair of the North American Transmission Forum, dedicated to excellence in performance and sharing industry best practices. He also was one of the eight industry experts selected to direct the North American Electric Reliability Corporation (NERC) investigation of the August 2003 Northeast/Midwest blackout. In 2014, he was elected to the National Academy of Engineering and is on the National Academies' Board of Environmental and Energy Systems. Prior to joining PJM, Mr. Boston was the executive vice president of the Tennessee Valley Authority, the nation's largest public power provider. In his 35 years at TVA, he directed divisions in transmission and power operations, pricing, contracts and electric system reliability. He served three years as chairman of the Southeastern Electric Reliability Council Board and serves on the boards of non-profits such as the Electric Power Research Institute and Grid Protection Alliance. He previously served on the NERC Stakeholders Board and was elected to the NERC Members Representative Committee. He holds a B.S. in engineering from Tennessee Technological University and an M.S. in engineering administration.

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Erica R. H. Fuchs is a Professor in the Department of Engineering and Public Policy at Carnegie Mellon University. Her research focuses on the development, commercialization and global manufacturing of emerging technologies, and national policy in that context. Over the past decade, Dr. Fuchs has been playing a growing role in national and international meetings on the future of advanced manufacturing, including serving as one of 23 invited participants in the President's Council of Advisors on Science and Technology workshop that led to the creation of the Advanced Manufacturing Partnership, and serving on the expert group that supported the White House in the 2016 Innovation Dialogue between the U.S. and China. She currently serves on the National Academies' National Materials and Manufacturing Board (NMMB), and the World Economic Forum's Future of Advanced Materials Global Agenda Council, and previously served on the National Academies' Committee on Harnessing Light: Capitalizing on Optical Science Trends and Challenges for Future Research. She is a member of the Advisory Editorial Board for *Research Policy*. Before coming to CMU, Dr. Fuchs completed her Ph.D. in engineering systems at M.I.T. in June 2006. She received her S.M. and her S.B degrees also from M.I.T. in technology policy (2003) and materials science and engineering (1999), respectively.

Supratik Guha is director of the Nanoscience and Technology Division at Argonne National Laboratory and a professor at the Institute for Molecular Engineering, University of Chicago. He came to Argonne in 2015 after spending 20 years at IBM Research, where he last served as director of physical sciences. At IBM, Dr. Guha pioneered the materials research that led to IBM's high dielectric constant metal gate transistor, one of the most significant developments in silicon microelectronics technology. He was also responsible for initiating or significantly expanding IBM's research and development (R&D) programs in silicon photonics, quantum computing, sensor-based cyberphysical systems, and photovoltaics. Dr. Guha is a member of the National Academy of Engineering, a fellow of the Materials Research Society and American Physical Society, and recipient of the 2015 Prize for Industrial Applications of Physics. He received his Ph.D. in materials science in 1991 from the University of Southern California, and a B.Tech in 1985 from the Indian Institute of Technology, Kharagpur. At Argonne and the University of Chicago, his interests are focused on discovery science in the area of nano-scale materials and systems for energy, sensing, and future information processing and their translation to applications.

Mark Jones is executive external strategy and communications fellow for The Dow Chemical Company. Prior to assuming this role, Dr. Jones' work focused on developing processes for producing battery materials, with emphasis on improving lithium-ion batteries. This work built on his experience with processing of inorganic materials, fuel cell development for portable power applications, and technology exploration. Much of Dr. Jones's professional work centered on the discovery, scale-up, and commercialization of catalytic technologies and on process improvements. Other recent efforts at Dow focused on overcoming the market and production hurdles faced by biomaterials. Dr. Jones served on the National Academies' Committee on Sustainable Development of Algal Biofuels. He completed postdoctoral work at the Cooperative Institute for Research in Environmental Science in Boulder, Colorado. He earned his Ph.D. in physical chemistry from the University of Colorado, Boulder and his B.S. in chemistry from Randolph-Macon College.

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Eric Landree is the associate research department director for the Engineering and Applied Sciences (EAS) Department and a senior engineer at the RAND Corporation, where he specializes in R&D strategic planning, the evaluation of emerging technologies, and research program evaluation. He has contributed to projects across the spectrum of national security, emerging technologies, and economic development and innovation. Recent work includes developing and piloting a method for evaluating the impact of nanotechnology research by the National Institute for Occupational Safety and Health (NIOSH), and creating a framework for identifying the roles and responsibilities of those implementing Department of Defense policies and identifying potential conflicts, ambiguities, gaps, and inconsistencies in those policies. Dr. Landree also supported NIOSH's preparations for evaluation of the relevance and impact of its R&D programs by the National Academies. Prior to joining RAND, he served as an American Association for the Advancement of Science Defense Science & Technology Policy Fellow in the Department of Defense Office of the Director for Defense Research and Engineering. After finishing graduate school, he earned a National Research Council Postdoctoral Fellowship, during which he conducted research on thin film material at the National Institute of Standards and Technology. Dr. Landree earned his Ph.D. in materials science and engineering from Northwestern University and his B.S. in physics from Allegheny College.

Gilbert Metcalf is a professor of economics at Tufts University and a research associate at the National Bureau of Economic Research. During 2011 and 2012, he served as deputy assistant secretary for environment and energy at the U.S. Department of the Treasury. Dr. Metcalf's current research focuses on policy evaluation and design in the area of energy and climate change. Other research has investigated the economics of energy security, incentives to drive investment in energy infrastructure, and policies to spur low-carbon energy technologies. Dr. Metcalf has edited three books and has contributed chapters to several books on energy and tax policy. He previously served on the National Academies' Committee on Health, Environmental, and Other External Costs and Benefits of Energy Production and Consumption. He received a Ph.D. in economics from Harvard University, an M.S. in agricultural and resource economics from the University of Massachusetts Amherst, and a B.A. in mathematics from Amherst College.

John Plaster is a managing director in the Global Power and Utilities Group and Head of Alternative Energy at Barclays, based in New York. Mr. Plaster has more than 18 years of investment banking experience with Barclays and Lehman Brothers. He has extensive experience with renewable energy companies (wind, solar, geothermal, and waste to energy), independent power producers, and regulated utilities across a wide spectrum of disciplines, including financial advisory, equity and equity-linked finance, leveraged finance, structured finance, restructuring, and commodities. Prior to joining Lehman Brothers, Mr. Plaster worked as an attorney in the Corporate Finance Group of Shearman & Sterling. He holds a J.D. degree, highest honors—Order of the Coif—from Vanderbilt University Law School, and a B.A. in economics, cum laude, from Wabash College.

Louis Schick is founding partner and chief technology officer at NewWorld Capital Group. His investments at NewWorld include energy infrastructure and production, such as several megawatt solar installations in the United States and Canada. Other investments include novel inverter technologies and air conditioning technology that reduces energy use and requires no

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chemical coolant. Mr. Schick has also worked as an independent consultant specializing in business applications of environmental technologies and as manager of private equity investments in clean energy companies. Prior to his investment work, he worked at General Electric, mainly at Corporate Research. In his various roles, he led evaluation of disruptive technologies for GE Energy, supported installation and repair of gas turbine power plants worldwide, served as developer and lead of a solid oxide fuel cell program and a low-carbon technologies program, carried out technical diligence on multiple fuel cell companies, and evaluated and ranked Gen III and Gen IV nuclear power cycles. Earlier, he was a product manager for MTI Micro Fuel Cells and ran the military product development team, where he managed several state and federal grant programs and developed patent applications. Mr. Schick holds technology patents in gas turbine parts, vehicle telematics, and other fields. He earned his M.S. in physics from Cornell University and his B.S. in physics from Union College.

Charles Shank is a senior fellow at the Howard Hughes Medical Institute. He previously served as director of the E.O. Lawrence Berkeley National Laboratory (LBNL) from 1989 until his retirement in 2004. Under his leadership, LBNL emerged as a leader in the field of supercomputing and joined with two other national labs to form the Joint Genome Institute, a major contributor to the decoding of the human genome. Dr. Shank also held a triple appointment as professor at the University of California at Berkeley in the Department of Physics, Department of Chemistry, and Department of Electrical Engineering and Computer Sciences. His research focused on ultrafast processes in solid state materials and molecular systems. Prior to serving with LBNL and Berkeley, Dr. Shank conducted research at Bell Labs, introducing the use of short laser pulses to the study of ultrafast events, allowing researchers to gain a better understanding of how energy is stored and transferred within materials. He has extensive experience serving on National Academies committees, most recently as co-chair for the Committee to Review the Quality of the Management and of the Science and Engineering Research at the Department of Energy National Security Laboratories—Phase II. Dr. Shank earned his Ph.D., M.S., and B.S. in electrical engineering from the University of California at Berkeley.

Stephanie S. Shipp is deputy director and research professor at the Social and Decision Analytics Laboratory (SDAL) at the Biocomplexity Institute of Virginia Tech. Dr. Shipp's work spans topics related to the use of *all* data to advance policy, the science of data science, and metropolitan analytics. She is leading and engaging in projects at the local, state, and federal level to assess data quality and use of new and traditional sources of data. Her research focuses on developing statistical methodology and tools for using administrative and other data to model the social condition quantitatively at scale. She conducts research that spans topics such as community, innovation, and defense analytics. She previously served as director of the Economic Assessment Office in the Advanced Technology Program at the National Institute of Standards and Technology. Dr. Shipp also led economic and statistical programs at the Census Bureau, the Bureau of Labor Statistics, and the Federal Reserve Board. She previously served on the National Academies' Committee on Assessing the Value of Research in Advancing National Goals and the Steering Committee for the Workshop on Future Directions for the National Science Foundation National Patterns of Research and Development Program. She is a fellow of the American Association for the Advancement of Science and an elected member of the International Statistics Institute. She is a fellow of the American Statistical Association, for

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which she has held several leadership positions. She was a member of the international advisory board for VINNOVA, Sweden's innovation agency, and led evaluation panels for the Swedish Research Council's Linnaeus Grant programs. Dr. Shipp received her Ph.D. in economics from The George Washington University and her B.A. in economics from Trinity University, Washington, D.C.

Scott Stern is David Sarnoff Professor of Management at the Massachusetts Institute of Technology (MIT) Sloan School of Management. His research in the economics of innovation and entrepreneurship focuses on entrepreneurial strategy, innovation-driven entrepreneurial ecosystems, and innovation policy and management. Recent studies include the impact of clusters on entrepreneurship, the role of institutions in shaping the accumulation of scientific and technical knowledge, and the drivers and consequences of entrepreneurial strategy. He has advised start-ups and other growth firms in the area of entrepreneurial strategy, and worked with governments and other stakeholders on policy issues related to competitiveness and regional performance. Dr. Stern co-founded the MIT Regional Entrepreneurship Acceleration Program, advised the development of the Social Progress Index, and served as lead MIT investigator on the U.S. Cluster Mapping Project. He is the director and co-founder of the Innovation Policy Working Group at the National Bureau of Economic Research. He previously served on the National Academies' Committee on the Impact of Copyright Policy on Innovation in the Digital Era and the Committee to Study the Future of Supercomputing. Dr. Stern holds a Ph.D. in economics from Stanford University and a B.A. in economics from New York University.

John Wall served as vice president and chief technical officer for Cummins Inc. In this role, he oversaw more than 6,000 engineers working to design internal combustion engines, power generation systems, and related technologies in Cummins technical centers around the world. Dr. Wall's earlier positions at Cummins included chief engineer, heavy-duty projects; director, emissions research; vice president, research & development; and vice president, advanced engineering and technology planning. Prior to joining Cummins, he held research and engineering positions at Chevron Research Company, most recently serving as unit leader of Diesel & Aviation Fuels Research. Dr. Wall's interests include advanced internal combustion engine design, emissions control and fuels, and engineering in a global environment. He serves on advisory boards at MIT and Purdue University. He previously chaired the National Academy of Engineering (NAE) Bernard M. Gordon Prize committee and has served on other NAE committees. Dr. Wall earned his S.B., S.M., and Sc.D. degrees in mechanical engineering from MIT.

Jay Whitacre (committee member until September 2016) is a professor of engineering and public policy and materials science and engineering at Carnegie Mellon University, and founder and chief technology officer of Aquion Energy, an energy storage technology firm.
Dr. Whitacre's research focuses on the implications of materials and technologies for the energy sector. These topics include the economics of scaled production, life-cycle analyses (including analyzing the "energy footprint" of manufacturing energy-related products), the implications of broad adoption of new energy technologies, large-scale energy storage devices, and concurrent engineering analyses of power systems. His materials science work focuses on synthesizing and implementing promising materials and device architectures for energy storage and generation technologies. His work resulted in the conception of a novel sodium-ion battery based on low-

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cost materials and related manufacturing techniques. In 2008 he founded the predecessor to Aquion Energy, which has grown to more than 130 employees since spinning out of Carnegie Mellon University in late 2009. Dr. Whitacre earned his Ph.D. in materials science from the University of Michigan and his B.A. in physics from Oberlin College.

Valerie Williams is senior program evaluator at the University Corporation for Atmospheric Research (UCAR), where she leads evaluation efforts for UCAR Community Programs and the National Center for Atmospheric Research (NCAR). Prior to working at UCAR, Dr. Williams worked at the RAND Corporation, where she led several government strategic planning and evaluation projects, including providing technical assistance to seven National Institute for Occupational Safety and Health (NIOSH) programs preparing for external review by the National Academies. In addition to evaluation, Dr. Williams participated in defense and intelligence projects at RAND, including research support for the Defense Advanced Research Projects Agency's (DARPA) Controlled Biological Systems program and technical assistance to the Federal Bureau of Investigation's (FBI) Inspections Division. Dr. Williams is a member of the American Evaluation Association (AEA) and currently serves on the AEA's Guiding Principles Task Force, which is charged with reviewing the principles that guide the professional practice of evaluation. She was invited to participate in the National Academies' Expert Evaluation Meeting for the review of the National Oceanic and Atmospheric Administration's (NOAA) Education Program in 2010 and has continued to provide evaluation guidance to NOAA Education as a senior evaluation consultant. Dr. Williams earned her Ph.D. in chemistry at New York University and completed postdoctoral training in biophysical chemistry in the Department of Pharmacology at the Mayo Clinic in Rochester, Minnesota. She earned her B.Sc. in chemistry from Emory University.

Peidong Yang is the S. K. and Angela Chan Distinguished Chair Professor in Energy and Professor of Chemistry in the Department of Chemistry and the Department of Materials Science and Engineering at the University of California, Berkeley. Dr. Yang's main research interest is in the area of one-dimensional semiconductor nanostructures and their applications in nanophotonics and energy conversion. Specific lines of inquiry include semiconductor nanowire laser, high performance nanowire-based thermoelectrics, and photovoltaics. In addition, Dr. Yang investigates the application of nanostructures in direct solar energy conversion to storable fuels such as hydrogen (H2) and other multi-carbon chemical fuels. He undertakes significant research on artificial photosynthesis. He was a founding member of and has served as a north center director at the Department of Energy's Joint Center for Artificial Photosynthesis. He also has valuable experience translating discoveries from the lab into commercializable products, having co-founded two start-ups based on his research—Nanosys Inc. and Alphabet Energy Inc. Dr. Yang earned his Ph.D. in chemistry from Harvard University and his B.S. in chemistry from the University of Science and Technology of China.

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Appendix B

Methods Used to Assess ARPA-E

This chapter explains the methods and data used in this report's assessment of ARPA-E; further detail is in Appendixes C and F. The methods used for the committee's operational and technical assessments were determined largely by the specific charges in the statement of task for this study (Box 1-1 in Chapter 1). As an example, Table B-1 presents the committee's translation of the first nine bulleted items in the statement of task into research/descriptive and evaluative/expert questions. The former questions were aimed at illuminating and explaining specific aspects of ARPA-E, whereas the latter were designed to determine the relative merit, worth, or significance of specific aspects of the agency. The first charge in the statement of task, for example—"Evaluate ARPA-E's methods and procedures to develop and evaluate its portfolio of activities"—implicitly embodies two questions: a research-oriented question focused on describing and understanding the methods and procedures ARPA-E uses to evaluate its portfolio of activities, and two evaluative questions focused on determining the sufficiency/adequacy of these procedures in relationship to the agency's mission and goals. As shown in Table B-1, there were often multiple research and evaluative questions for a single task, so questions were prioritized according to their relative importance. Next, the committee determined the appropriate methods and corresponding data sources for addressing these questions. The list of data sources was reviewed for redundancy and became the basis for the committee's data request to ARPA-E (Appendix E). Tables B-2, B-3, and B-4 provide examples of the committee's mapping of research and evaluative questions to methods and data sources for charges 1, 6, and 9 in Table B-1.

TABLE B-1 Statement of Task and Corresponding Research and Evaluative Questions for the Operational Assessment

Statement of Task	Corresponding Research Question(s)
1. Evaluate ARPA-E's methods and procedures to develop and evaluate its portfolio of activities.	*Research/Descriptive:*
	1. What are ARPA-E's methods and procedures for developing and evaluating its portfolio of activities? Have they continued to evolve? If so, what are the factors that contributed to their evolution?
	Evaluative/Expert:
	2. Are ARPA-E's methods and procedures for developing and evaluating its portfolio of activities sufficient for identifying cutting-edge technology projects?

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	3. Have the methods and procedures used by ARPA-E to develop and evaluate its portfolio of activities resulted in measurable contributions to ARPA-E's mission or stated goals?
2. Examine the appropriateness and effectiveness of ARPA-E programs for providing awardees with nontechnical assistance, such as practical financial, business, and marketing skills.	*Research/Descriptive:*
	1. What are ARPA-E's activities to provide awardees with nontechnical assistance, such as practical financial, business, and marketing skills?
	2. Compared with awardees that receive less or minimal nontechnical assistance, are awardees with more technical assistance experiencing different outputs and outcomes?
	Evaluative/Expert:
	3. To what extent has the nontechnical assistance, such as practical financial, business, and marketing skills, provided to awardees helped them to bring their technology to market? Helped their technologies to contribute to ARPA-E's mission or stated goals?
	4. Has ARPA-E provided the appropriate practical financial, business, and market skills for the current challenges and barriers in the technology and commercialization arena?
3. Assess ARPA-E's recruiting and hiring procedures to attract and retain qualified key personnel.	*Research/Descriptive:*
	1. What are ARPA-E's recruiting and hiring procedures?
	2. How do the qualifications of key personnel within ARPA-E compare with those of similar personnel within other departments or agencies within DOE?
	Evaluative/Expert:
	3. To what extent have ARPA-E's recruiting procedures been successful at attracting and retaining the best and brightest to key roles such as deputy directors? Program directors?
4. Examine the processes, deliverables, and metrics used to assess the short- and long-term success of ARPA-E programs.	*Research/Descriptive:*
	1. What processes, deliverables, and metrics are used by ARPA-E to assess the short- and long-term success of its programs in contributing to ARPA-E's mission or stated goals (or means)?
	Evaluative/Expert:
	2. How effective have the processes, deliverables, and metrics been in ensuring that programs are meeting their identified goals? In identifying challenges or difficulties that inhibit ARPA-E's ability to contribute to its mission or goals? In helping programs to stay on track?
5. Assess ARPA-E's coordination with other federal agencies and alignment with long-term DOE objectives.	*Research/Descriptive:*
	1. What process does ARPA-E use to coordinate with other federal agencies (including other parts of DOE)?
	2. What other federal agency programs does ARPA-E coordinate with?
	3. How does ARPA-E leverage work from other federal agencies and address unintentional duplicative work?
	Evaluative/Expert:

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	4. How well do ARPA-E's mission and goals align with long-term DOE objectives?
	5. Has ARPA-E proactively looked for ways to coordinate its long-term goals with other federal agencies? If so, how successful have these efforts been?
6. Evaluate the success of the focused technology programs in spurring formation of new communities of researchers in specific fields.	*Research/Descriptive:*
	1. What is ARPA-E's process for creating focused technology programs?
	Evaluative/Expert:
	2. Have the focused technology programs spurred the formation of new communities of research? If so, how sustainable have these communities been?
	3. What, if any, significant products and technologies have emerged from these communities of researchers?
	4. How have the products and technologies from these communities of researchers contributed to ARPA-E's mission or stated goals?
7. Provide guidance for strengthening the agency's structure, operations, and procedures.	*Research/Descriptive:*
	1. Outside of DARPA, what are some appropriate models for ARPA-E to consider for strengthening its structure, operations, and procedures?
	Evaluative/Expert:
	2. Based on the findings from this committee, where are areas for improving how the agency's structure, operations, and procedures contribute to its mission and stated goals?
8. Evaluate, to the extent possible and appropriate, ARPA-E's success at implementing successful practices and ideas utilized by the Defense Advanced Research Projects Agency (DARPA), including innovative contracting practices.	*Research/Descriptive:*
	1. What practices and ideas utilized by DARPA have been most useful and relevant for ARPA-E?
	Evaluative/Expert:
	2. How successful has ARPA-E been in using practices and ideas utilized by DARPA to create an infrastructure to support high-risk/high-payoff programs and projects and contribute to ARPA-E's mission and stated goals?
9. Reflect, as appropriate, on the role of ARPA-E, DOE, and others in facilitating the culture necessary for ARPA-E to achieve its mission.	*Research/Descriptive:*
	1. What challenges, if any, does ARPA-E face from DOE in developing an innovative and nimble culture to enable it to achieve its mission?
	Evaluative/Expert:
	2. How has ARPA-E created a sustained innovative and nimble culture?
	3. Can aspects of the ARPA-E model be transferred to DOE? If so, what is transferable?

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TABLE B-2 Methods and Data Sources for Questions under Statement of Task Charge 1 (Evaluate ARPA-E's methods and procedures for developing and evaluating its portfolio of activities.)

Research/Evaluation Question	Methodological Approach	Data Sources
What are ARPA-E's methods and procedures for developing and evaluating its portfolio of activities?	• Review of program documentation, including strategic planning and documents that codify processes • Interviews with ARPA-E program directors	ARPA-E: • Archival ARPA-E planning documents FOAs: • Names of program directors for gathering interview data
Are ARPA-E's methods and procedures for developing and evaluating its portfolio of activities sufficient for identifying cutting-edge technology projects?	• Expert interviews, particularly with those who are knowledgeable of mechanisms to support and foster innovation • Trend analysis of portfolio	General: energy system—major opportunities for contribution (from experts & literature): • ARPA-E: project funding data (names, projects, technologies that emerged)
Have the methods and procedures used by ARPA-E to develop and evaluate its portfolio of activities resulted in measurable contributions to ARPA-E's mission or stated goals?	Documenting of program development cycle to: • Lay out hypothesized path for how portfolio of activities should lead to goals • Collect evidence to validate intended pathway	General and ARPA-E: • Publications, patents, commercialized outcomes, revenues, novel collaborations, communities built • Names of key stakeholders for interviews about outcomes

NOTE: FOA = Funding Opportunity Announcement.

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TABLE B-3 Methods and Data Sources for Statement of Task Charge 6 (Evaluate the success of the focused technology programs in spurring the formation of new communities of researchers in specific fields.)

Research/Evaluation Question	Methodological Approach	Data Sources
1. What is ARPA-E's process for creating focused technology programs?	Review of program documentation on focused programs: • Comparison with the open solicitation process to get a better idea of attributes of focused programs • Interviews with program directors for focused programs—particularly comparison of descriptions from earlier years (e.g., 2010) with more recent descriptions to determine changes in process	ARPA-E: • Program documentation on the focused programs (e.g., solicitations, program development cycle, timelines, decision criteria) • Names of program directors for interviews
2. Have the focused technology programs spurred the formation of new communities of research? If so, how sustainable have these communities been?	• Interviews with program directors, attendees at Energy Innovation Summit; literature review on communities of practice; metrics for or indicators of sustainability • Quantification of whether ARPA-E funding (versus other forms of funding) (1) increases the proportion of novel collaborators and (2) changes network structure in the larger community; measured through (1) authors listed on proposal submissions and (2) broader patent and publication co-authorship networks	ARPA-E: • Names of program directors • Attendees at Energy Innovation Summit, programs and agendas from meetings • Lists of potential collaborations that have formed and can be linked back to ARPA-E meetings, proposals (funded/nonfunded) that show evidence of collaboration
3. What, if any, significant products and technologies have emerged from these communities of researchers?	• Archives, quantitative data • Expert review of technologies	• General/ARPA-E: publications, patents • ARPA-E: technologies and/or commercialized outcomes, revenues, funded proposals, submissions resulting from or linked to meetings

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TABLE B-4 Methods and Data Sources for Statement of Task Charge 9 (Reflect, as appropriate, on the role of ARPA-E, DOE, and others in facilitating the culture necessary for ARPA-E to achieve its mission.)

Research/ Evaluation Question	Methodological Approach	Data Sources
1. What challenges, if any, does ARPA-E face from DOE in developing an innovative and nimble culture to enable it to achieve its mission?	• Interviews with program directors, director, deputy directors (past and present) • Views from DOE programs that have worked with ARPA-E • DARPA interviews potentially to identify challenges it faced and determine whether similar to ARPA-E	• General: internal DOE literature or circulars • ARPA-E: Names of past and present program and deputy directors, personnel within ARPA-E that may have DARPA associations
2. How has ARPA-E created and sustained an innovative and nimble culture?	• Literature review on organization elements most commonly associated with an innovative and nimble culture; analysis to determine the extent to which these elements are present • Interviews to develop a working hypothesis on critical elements for ARPA-E culture	• ARPA-E: Names of ARPA-E staff or personnel who are knowledgeable about and perhaps fostered the development of the organizational culture
3. Can aspects of the ARPA-E model be transferred to DOE? If so, what is transferable?	• Focus group with ARPA-E management • Focus group with different DOE program managers	• General: names of DOE managers who are knowledgeable of ARPA-E • Names of ARPA-E managers who could participate in focus groups/interviews

As summarized in Chapter 1, the committee formed four subgroups based on the methods to be used: (1) the Internal Operations Qualitative Data Team, which gathered and analyzed qualitative data, including information obtained through interviews with current and former ARPA-E personnel and U.S. Department of Energy (DOE) officials and discussions with stakeholders at ARPA-E events, such as program kickoffs and interim meetings; (2) the Case Study Team, which conducted three types of case studies (a single focused program, a portfolio of 63 energy storage projects, and 10 individual projects); (3) the Internal Operations Quantitative Data Team, which accessed internal, proprietary ARPA-E data and reported aggregated findings from these data; and (4) the External Quantitative Data Team, which obtained data from external sources, such as the U.S. Patent and Trademark Office's (USPTO)

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patent database, publications, and other sources. The sections below describe these methods and the data used in greater detail. As shown in Tables B-2, B-3, and B-4, the data for the research questions were to be obtained primarily from such sources as literature reviews, question-and-answer sessions with ARPA-E staff during panel presentations at committee meetings, conversations with ARPA-E awardees at agency events, interviews with former agency staff, case studies, and event observations. The evaluative questions were to be addressed through the expert assessment of committee members.

The committee formulated a data request to ARPA-E that included both internal, proprietary information about firms and agency personnel and processes and nonproprietary information (see Appendix E). ARPA-E worked cooperatively with the committee to provide the requested data. The committee worked with independent consultants to analyze these data; the data were anonymized before being provided to the consultants. The committee directed the consultants to perform certain analyses of the anonymized data so that aggregated results could be presented to the entire committee with no risk of revealing propriety business information. The consultants' reports are included in Appendix F. Where confidentiality was a concern, ARPA-E allowed the consultants to work in agency offices to gather the data, which were then presented to the committee in aggregated form.

QUALITATIVE DATA ANALYSIS

Individual Consultations

Semistructured individual consultations were conducted with former ARPA-E program directors and DOE officials who had either worked with ARPA-E during their career or been involved in collaboration for ARPA-E projects. Table B-5 provides a list of the individuals the committee consulted during the course of its assessment.

TABLE B-5 Consultations Conducted for ARPA-E Assessment

Consulted	Title	Date
Cadieux, Gena	DOE, Deputy General Counsel for Transactions, Technology, & Contractor Human Resources	1/15/2016
Chalk, Steven	Deputy Assistant Secretary for Renewable Energy	1/5/2016
Chu, Steven	Secretary of Energy	2/15/2016
Danielson, David	DOE, Assistant Secretary of Energy Efficiency & Renewable Energy (EERE), and Co-Founder/Employee #1 ARPA-E	12/3/2015
Friedmann, Julio	DOE, Principal Deputy Assistant Secretary for the Office of Fossil Energy	1/6/2016
Gur, Ilan	DOE, former ARPA-E Program Director, currently founder of Cyclotron Road	9/22/2015
Hoffman, Patricia	DOE Assistant Secretary for the Office of Electricity (OE)	1/6/2016
Howell, David	DOE, Vehicle Technology Office, Program Manager, and currently Manager, Energy Storage R&D at DOE	1/27/2016
Johnson, Mark	DOE, Director of the Advanced Manufacturing Office (AMO) and former Program Director at ARPA-E	2/9/2016
Kolbe, Ingrid	DOE, Director of the Office of Management	1/15/2016

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Le, Minh	DOE, Deputy Director, Solar Energy Technologies Office	1/27/2016
Prashar, Ravi	Lawrence Berkeley National Laboratory (LBNL), Division Director of Energy Storage and Distributed Resources Division	1/29/2016
Ramamoorthy, Rameesh	LBNL, Materials Scientist, Department of Materials Science and Engineering, University of California, Berkeley	1/29/2016
Simon, Horst	LBNL, Deputy Director	1/29/2016
Smith, Christopher	DOE, Assistant Secretary for Fossil Energy	1/6/2016

The questions discussed in these consultations were drawn primarily from the statement of task (see Table B-1) and focused on the following key topics:

- recruiting and hiring procedures used to attract and retain talented personnel;
- coordination with other federal agencies and alignment with DOE objectives;
- guidance for strengthening ARPA-E's structure, operations, and procedures;
- the role of ARPA-E, DOE, and others in facilitating the culture necessary for ARPA-E to achieve its mission; and
- lessons learned from the operation of ARPA-E that may apply to other DOE programs and factors that Congress should take into consideration in determining the agency's future.

Notes from the discussions were analyzed using the qualitative data management software ATLAS.ti (Muhr, 2004). Questions discussed in the consultations provided the basis for the preliminary list of codes used for this analysis. This first iteration of coding was descriptive. Each set of discussion notes (in some cases, more than one set of notes was taken for each interview) was coded using the consultation questions, enabling the committee to categorize the various responses. These codes were later refined and grouped within a "people, process, and culture" framework, which essentially served as the parent code structure. This framework emerged from subgroup review and discussion of the notes from the consultations and reflected a common response to the question of important factors related to ARPA-E's success, and was used for the initial outline of the chapter of this report on ARPA-E's internal operations (Chapter 3). Because the discussions centered on ARPA-E operations and DOE's relationship with the agency, the codes were categorized into "Internal to ARPA-E" and "Intersection of ARPA-E with DOE," as shown in Table B-6.

TABLE B-6 Categorization of Questions Used for Individual Consultations

Internal to ARPA-E	Intersection with DOE
ARPA-E Culture: confrontation	Coordination with DOE
ARPA-E Culture: risk	Coordination with DOE: challenges
ARPA-E Process: active management	DOE Culture: ARPA-E practices
ARPA-E Process: budgetary control	DOE Culture: barriers to adopting ARPA-E practices
ARPA-E Success	DOE Culture: exportability of ARPA-E practices
ARPA-E People: attracting and hiring talent	DOE People: hiring practices
ARPA-E People: recruiting	DOE Process: ARPA-E recommendations
	Nontransferrable ARPA-E practices

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The second iteration of coding was more interpretive, as the committee specifically linked the consultation notes back to the statement of task. The statement of task provided an organizational structure that made it possible to expand these codes as needed and identify important themes related to the key areas listed earlier. Figure B-1 provides an example of how the themes relate back to the statement of task.

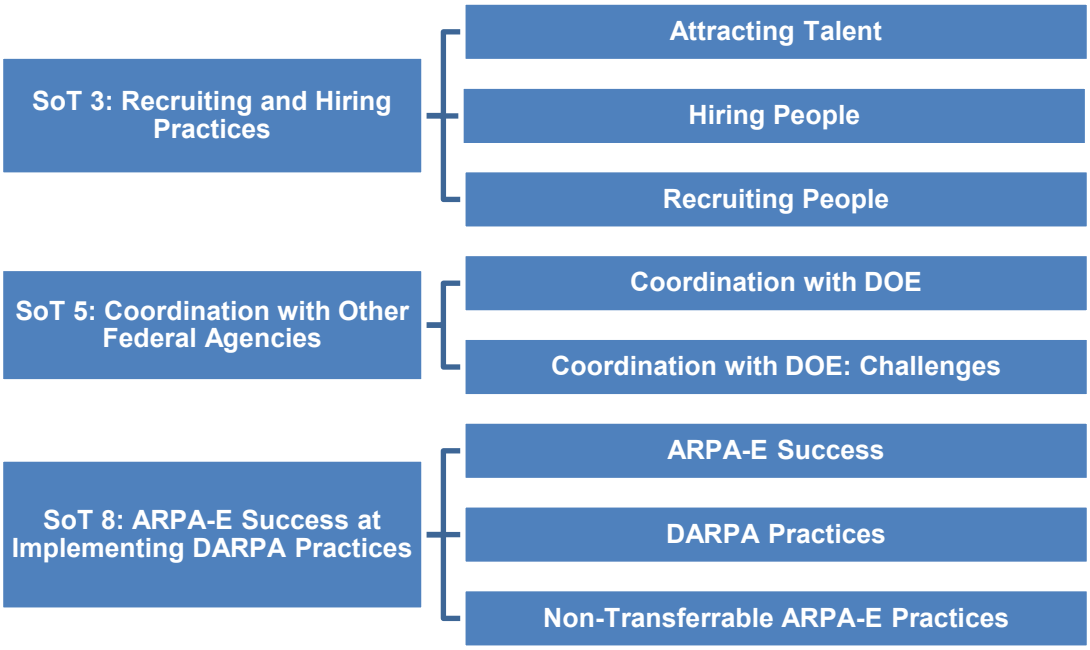

FIGURE B-1 Relationship between statement of task charges and themes that arose during consultations. NOTES: SoT = statement of task. Numbers refer to the specific charges in the SoT listed earlier in Table B-1.

Event Observation

In addition to the semistructured interviews discussed above, committee members across all of the subgroups attended the ARPA-E events listed in Table B-7 and talked informally with key stakeholders.

TABLE B-7 ARPA-E Events Attended by Committee Members

Event	Location	Date
Transportation Fuels Workshop	Denver, CO	Aug. 27–28, 2015
Methane Opportunities for Vehicular Energy (MOVE) Annual Meeting	Denver, CO	Sept. 14–15, 2015
Advanced Research In Dry cooling (ARID) Program Kickoff Meeting	Las Vegas, NV	Sept. 29–30, 2015
Accelerating Low-cost Plasma Heating and Assembly (ALPHA) Program Kickoff Meeting	Santa Fe, NM	Oct. 14, 2015
Generators for Small Electrical and Thermal Systems (GENSETS) Program Kickoff Meeting	Chicago, IL	Oct. 21–22, 2015
Annual Energy Innovation Summit, 2016	National Harbor, MD	Mar. 1, 2016

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Committee members developed and used an observation protocol to standardize the information gathered during each event. This protocol included two sections for comment—the overall event function and the energy sector issue addressed. The event function section included the following dimensions on which committee members were asked to provide comments and ratings:

- **Program director's program vision**—Is there a clear vision for the program? Are the program director's authority and leadership in this area apparent?
- **Participation and representation**—Are attendees actively participating? Are key stakeholders present? Are multiple perspectives represented? Are differences in perspectives and opinions openly shared?
- **Organization and structure**—Is there a clear agenda? Is the event organized and well planned? Are objectives appropriate for time allowed?
- **Results and actions**—Did the event have clear outcomes? Are the results relevant? Are next steps and action items are clear? Were the overall purpose and objectives for workshop met?

The energy sector section was designed to capture more substantive information on projects and their potential impact. Committee members were asked to comment on and rate the following:

- **Coherent statement of the energy problem to be solved**—Was the energy problem easily understood and well researched?
- **Potential impact on ARPA-E's mission**—Was there a clear description and understanding of the impact of the agency's goals for reducing imported energy, enhancing energy efficiency, and reducing energy-related emissions?
- **Transformative and disruptive approach**—Was there a clear understanding of the transformative aspects of the technology on which the event focused? Was the approach innovative and unlikely to be considered for investment through traditional DOE programs?
- **Positioning technology for market**—Was there a clear plan for uptake of the technology by the market?

Data captured through these observational protocols were shared with the full committee and deliberated.

Case Studies

Case studies of one focused program, electrical storage battery projects from several focused programs, and individual projects were undertaken to provide descriptive examples of ARPA-E's operations and the technical outcomes of its projects and programs. The committee cautions that these cases studies may not be representative of all ARPA-E projects because of the limited number of case studies that was feasible to conduct. Nonetheless, the case studies served as a key element of the committee's weighing of the evidence on the operations and technological impacts of ARPA-E.

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As discussed in Chapter 1, ARPA-E had been in existence for 6 years at the time of this evaluation, which, relative to the life span of energy technologies, is relatively young (Powell and Moris, 2002).[1] Thus, the findings from these case studies may not fully reflect the maturation of the respective technologies and their subsequent potential impact. Moreover, most ARPA-E projects are funded for roughly 3 years, so that at the time of this assessment, there were at most two cohorts of cases to examine. Therefore the focus was on evaluating ARPA-E's operations to assess whether the projects selected (1) met the agency's criterion of funding technologies with the potential to be transformational, (2) fell within a white space that is not being funded by industry because of technical and financial uncertainty, and (3) were in accordance with ARPA-E's mission.

Experts from the committee provided guidance on the meaning of transformative technologies, which enabled assessment of the potential impacts of ARPA-E's projects. This guidance included one or more of the following elements:

- evidence of market penetration and ultimately market domination;
- a scientific discovery or technological development that was previously considered impossible or was totally unexpected, often from blue-sky research (although a major scientific discovery or engineering breakthrough is not sufficient to produce a transformative technology, as the transformative nature of a technology ultimately can be measured only in the marketplace or society); and/or
- evidence of deployment along a commercialization pathway as part of this transformation.

The case studies address in full or in part three specific charges in the statement of task, shown on the lefthand side of Figure B-2, and covered topics shown on the righthand side of the figure.

As noted above, the committee conducted three types of case studies: (1) a single program (SWITCHES [Strategies for Wide-Bandgap, Inexpensive Transistors for Controlling High-Efficiency Systems]), (2) a portfolio of 63 projects related to energy storage technologies, and (3) 10 individual projects. The case studies are described in Chapter 4 and presented Appendix C.

[1]The Advanced Technology Program is similar to ARPA-E, so the commercialization timelines are expected to be similar. For successful technologies, the commercialization timing varies. The timeline for information technology (IT) projects is roughly 1 year after funding ends. Electronics technologies have some early applications, but then they experience a steep rise in activity in the second year after funding ends, followed by a fall-off more rapid than that in any other technology area except IT. Materials-chemistry and manufacturing-based applications build up somewhat more slowly and tail off more slowly than electronics and IT. Biotechnologies have an initial spurt of activity in the second year after funding ends, then have another spurt 5 or more years later.

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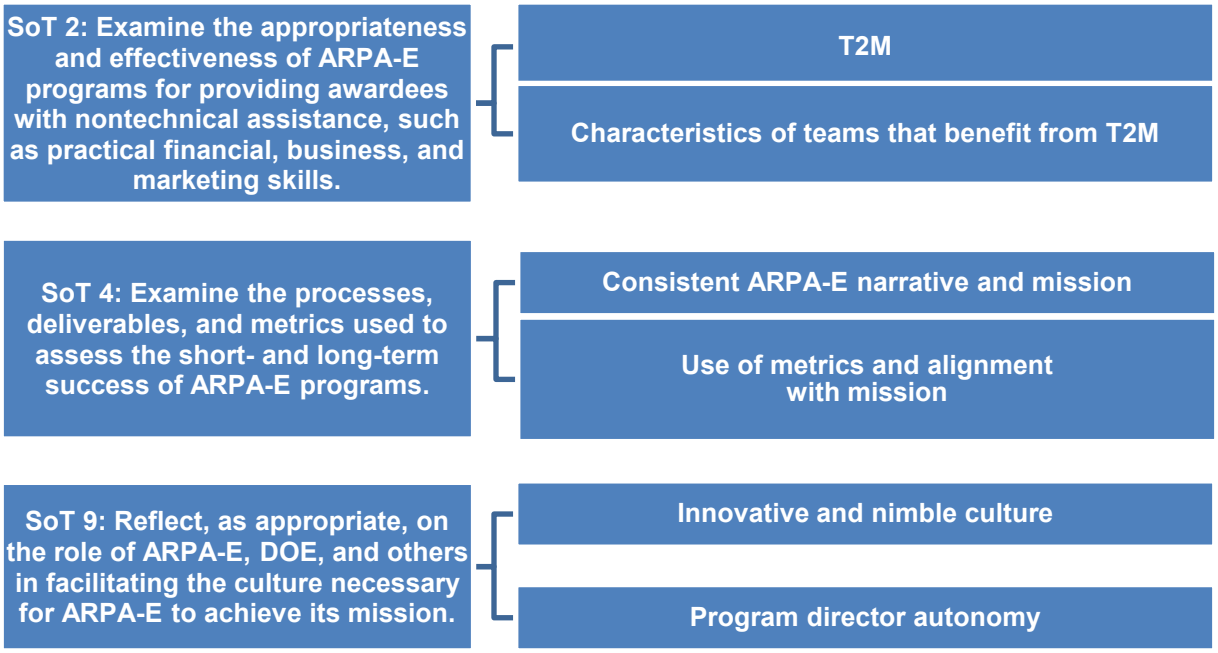

FIGURE B-2 Statement of task charges and topics covered by case studies.
NOTE: SoT = statement of task; T2M = technology-to-market.

The committee undertook a blend of illustrative and explanatory case studies.[2] Case study information was collected through review of ARPA-E materials (program descriptions, funding announcements, and other multimedia information) and external materials (primarily websites, popular press and journal articles, and occasionally Securities and Exchange Commission filings), as well as various metrics and other quantitative data. Information also was obtained from public presentations made to the committee by ARPA-E program directors and through interactions with performers at various venues, including the annual Energy Innovation Summit.

Semistructured conversational interviews were conducted to ensure that similar information would be collected during each interview while also allowing unique or interesting ideas to emerge, referred to as "surprises." The case study write-ups in Appendix C reflect an attempt to address the interview questions so patterns and differences could be identified across case studies (Caudle, 1994). The External Quantitative Data Team provided other indicators, such as counts of publications and patents. In a few cases, discussions were held with the ARPA-E program directors who oversaw the case study projects.

Each case study interview involved the ARPA-E performer (generally the project's principal investigator) and often at least one other project team member. The committee team consisted of two members (a scientist or engineer and a social scientist) and typically one or two members of the National Academies staff involved in the study. The interviews were held by phone and

[2] Illustrative case studies are anecdotes that bring "immediacy, convincingness, and attention-getting" qualities to a study (GAO, 1990). They are often used to complement quantitative data by providing examples of overall findings. Morra and Friedlander (n.d.) note that illustrative case studies tend to have a narrower focus than explanatory cases. Explanatory case studies explain the relationships among program components and help identify performance measures or pose hypotheses for further evaluation research. Explanatory case studies are designed to test and explain causal links when the complexity involved cannot be captured by a survey or experimental approach (Yin, 1984, 2013).

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lasted from 30 to 60 minutes. The case studies also include an expert assessment of the technology developed during the project and its potential to be transformative, provided by a committee member.

Generally, the technical committee member led the discussion, while the social scientist asked clarifying questions. The discussion covered the following topics: the state of the research before applying to ARPA-E; reasons for responding to the FOA; examples of interactions with ARPA-E program directors and the T2M team; and other thoughts or insights the performer wished to provide. Box B-1 presents the list of questions used as a guide for the conversations with performers across the case studies to ensure coverage of a consistent set of topics.

BOX B-1
Case Study Questions for ARPA-E Performers

1. What was the state of your research before you applied to ARPA-E (your ideas, funding, research staff)?
2. Why did you respond to the Funding Opportunity Announcement? Did it change your way of solving these challenges? Why did this represent an opportunity for you?
3. Please share one or two examples of interactions with your program director and/or T2M team that led to changes in your approach to your research or commercialization pathways. (Might be useful to gain context by asking about their experiences with commercialization of technology.)
4. ARPA-E programs begin with high-level performance targets, and your project has specific technical stretch metrics.
   - What is the connection between program and project metrics, if any?
   - Describe what you accomplished during the project vis à vis the metrics.
   - Did you learn things that modified the targets during project execution?
5. What else would you like to tell us about your experiences with ARPA-E?

As time permitted, other topics were discussed, such as the performer's plans to move the technology to the next stage of research or to the market, key lessons from the project, mechanisms for industry interaction and feedback concerning the technology, examples of how ARPA-E interactions led to new collaborations that would likely not have occurred, and the performer's experience with the ARPA-E Energy Innovation Summit. Each case study was reviewed and approved by the performers who had participated in its development.

INTERNAL AND EXTERNAL QUANTITATIVE METHODS

Quantitative Analysis of Data from ARPA-E's Internal Project Management System

A central question in the statement of task for this study was to what degree ARPA-E has internalized active management practices similar to those utilized by DARPA in its selection, development, and evaluation of projects. In addition to determining whether ARPA-E used active management practices, the committee sought to assess whether these practices had an impact on internal and external measures of success of the projects. To address these questions, the committee worked with external consultants to investigate ARPA-E's practices for project

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selection and management and their impact on project outcomes through a detailed analysis of internal data provided by the agency. The consultants delivered a working paper (Goldstein and Kearney, 2016[3]) that provides detailed analysis.

The quantitative analysis of ARPA-E's project management data conducted by the consultants addresses the following charges in the statement of task: (1) evaluate ARPA-E's methods and procedures for developing and evaluating its portfolio of activities; (2) examine the appropriateness and effectiveness of ARPA-E programs for providing awardees with nontechnical assistance, such as practical financial, business, and marketing skills; (3) examine the processes, deliverables, and metrics used to assess the short- and long-term success of ARPA-E programs; and (4) evaluate, to the extent possible and appropriate, ARPA-E's success at implementing successful practices and ideas utilized by DARPA, including innovative contracting practices.

To characterize and better understand the range of practices used for active management at ARPA-E, Goldstein and Kearney (2016) analyzed a large set of ARPA-E data consisting of anonymized information for all concept paper applications; full-proposal applications; review scores for all full proposals; binary selection information; quarterly progress reports for each project; and outcome metrics associated with each project, including patent applications, publications, and a series of indicators for market engagement (e.g., follow-on funding).

Using the information on external reviewer scores, the consultants determined which projects would have been funded using those scores alone and determined which projects were selected using ARPA-E's active selection process, which, as discussed previously, gives the program manager significant discretion (as overseen by the Merit Review Board) to select projects. The consultants compared the outcomes of funded projects with lower external scores and those of projects with higher scores.

The consultants collected information on various characteristics of program managers, such as the year they received their undergraduate degree and the number of years they spent in either an industry or academic position before joining ARPA-E. The consultants also looked at the number of program director changes and the rate of such changes (number of changes divided by project duration in years). Additionally, the consultants calculated the fraction of a project managed by each program director.

The consultants also gathered data from ARPA-E's quarterly reporting requirement for each project regarding changes in a project's negotiated milestones to determine whether program managers were using active program management. Program managers can adjust project milestones, budgets, and timelines. Milestone changes may be recorded as a change in the text of a milestone, or the milestone itself may be deleted and replaced with a new one. The consultants were able to observe only deletions/new milestones and not milestone revisions under the same milestone number. Thus, the information on milestone changes gathered by the consultants likely underestimates the number of milestone changes.

The data collected on project (or project manager) characteristics was then compared with various internal and external outcome measures, including an internal status update on the project's performance along technical, cost, schedule, and overall performance. The external outcome measures included publications. As discussed further below, the consultants also created a publications dataset collected by searching Web of Science (WOS) for all publications through December 31, 2015, citing the award or work authorization number for an ARPA-E

[3]This working paper, provided in Appendix F, includes a more detailed description of the data collected, the methodologies used, the analysis, and the authors' conclusions.

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project (see Goldstein, 2016, for further detail on the methods used to collect publication data). Highly cited publications are defined as publications with more citations than the top 1 percent of most cited papers in a given research field in a given year. Top journal publications are defined as publications in the top 40 journals in science and engineering fields, ranked by number of highly cited papers. Energy journal publications are those from the subject category Energy and Fuels. The consultants created variables in the projects dataset for the number of total publications resulting from a project, as well as the number of each of the above three types of publications. The methods used in collecting information on publications, patents, and market engagement are explained in more detail in the next section.

An additional external outcome measure looked at patents. As part of their cooperative agreement, awardees are required to acknowledge ARPA-E support in any patents, as well as to report intellectual property to DOE. ARPA-E has, in collaboration with the DOE General Counsel's office, collected data on invention disclosures, patent applications, and patents reported as a result of each ARPA-E award. The consultants obtained the count data on these outcomes for each award through the end of 2015, as well as the filing date of the patent applications and the issue date for the patents.

Finally, the external outcome measures looked at market engagement metrics as tracked by ARPA-E. Each spring, to coincide with the annual Energy Innovation Summit, ARPA-E publishes a list of projects that have (1) received follow-on private funding, (2) generated additional government partnerships, and (3) led to the formation of companies.[4] In addition, the consultants obtained separately from ARPA-E a list of awards that have led to (4) initial public offerings (IPOs), (5) acquisitions, or (6) commercial products. These market engagement metrics are those reported by awardees as being directly attributable to ARPA-E support as of February 2016. They were used to create dummy variables for each of the six market engagement metrics as well as a dummy for at least one market engagement metric having been met. The consultants also obtained data on the amount of private funding reported by the awardee in each year and in total.

Finally, the consultants created two additional metrics to combine the three categories of external outputs that also were used in the external data analysis described below—publications, inventions, and market engagement. The first was a "minimum standard" variable that captured whether a project had at least one publication, at least one patent application, or some form of market engagement (as defined by the six market engagement metrics described in the preceding paragraph). The second was a dummy variable for projects that had all three of the above-mentioned metrics.

Quantitative Analysis of Publicly Available Data

The quantitative analysis of publicly available data addressed parts of the statement of task related to the technical assessment: to identify where ARPA-E projects have made an important difference, and to help assess the performance of the portfolio of awards and evaluate whether and to what extent the portfolio has helped ARPA-E achieve its goals. Committee members directed a consultant to conduct a detailed analysis of the impact of ARPA-E compared with that of DOE's Office of Science and Office of Energy Efficiency and Renewable Energy (EERE). The consultant created a dataset of all awards offered by the three agencies using publicly

[4]Company formation for these purposes includes start-up company awardees for which the ARPA-E award was their first funding.

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available data. This dataset links award-level specifications for recipient type, amount of funding, and project length to publicly available outcomes credited to each award. The sample includes data on patents, patent quality, publications, and publication quality.

The consultant created the dataset using award data from the Data Download page of USAspending.gov. Run by the Department of the Treasury, USAspending.gov provides publicly accessible data on all federal awards, in accordance with the Federal Funding Accountability and Transparency Act of 2006.[5] The consultant downloaded all transactions made to prime recipients of grants or "other financial assistance" from DOE in fiscal years (FY) 2009–2015. These transactions include grants and cooperative agreements and exclude contracts and loans.

The exclusion of contracts is important to note because contracts are the primary mechanism through which DOE funds research and development (R&D) at the national laboratories. Legally defined, contracts are used for government procurement of property or services, while grants and cooperative agreements are used to provide support to recipients, financial or otherwise.[6] A cooperative agreement is different from a grant in that it entails "substantial involvement" between the agency and the recipient. Given that ARPA-E uses cooperative agreements as its primary mechanism for distributing funds, grants and cooperative agreements were the most relevant choice for this comparison.

Each transaction downloaded from USAspending.gov is associated with an award ID (or award number), which is a string of up to 16 characters; multiple transactions are associated with most awards. Award numbers begin with the prefix "DE," followed by a two-letter code indicating the office or program where the award originated. This system for assigning award numbers appears to have become standard for DOE assistance beginning in FY 2009.

Many of the transactions are duplicates; therefore, the data were consolidated to a single entry reflecting the total funding per award. Further modifications were necessary to limit the dataset to those awards related to energy R&D. The consultant then categorized each award based on its Catalog of Federal Domestic Assistance (CFDA) number and excluded those awards not related to R&D activities, such as block grants to city governments for energy-efficiency upgrades.

The resulting dataset (referred to as the "DOE dataset") contained 5,896 awards, 263 of which were from ARPA-E. None of the awards for FY 2009 were from ARPA-E as the first ARPA-E awards began in December 2009. Together, the Office of Science and EERE produced a majority (80 percent) of the awards in the dataset. The consultant reported the mean and standard deviation of each variable (patents, patent quality, publications, and publication quality) by office.

As noted, publication outputs for DOE awards were obtained from WOS, a subscription-based product from Thomson Reuters with information on scientific publications and citations. The dataset was derived from the WOS Science Citation Index-Expanded. All searches were automated using the WOS application programming interface (API). For each award in the DOE dataset, the consultant searched for the award number in the Funding Text field of the WOS publication records. Each search returned a list of all articles and conference proceedings (collectively referred to here as papers) that acknowledged that award number. The consultant included bibliographic data for all papers published through December 31, 2015, that acknowledge an award in the DOE dataset. Separate searches were submitted to obtain the references within each paper, as well as the citations made to each paper between April 1, 2009,

[5] *Federal Funding Accountability and Transparency Act of 2006*, 109th Cong., 2d sess. (2005-2006).
[6] 41 U.S.C. 501 et seq.

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and December 31, 2015. The publication outputs of each award were added to the DOE dataset. A paper-level dataset also was created, containing only those papers that acknowledge an award in the DOE dataset. There were 9,152 papers in this set, 56 of which jointly acknowledge two DOE offices; 561 papers acknowledge an ARPA-E award. The committee notes that there are potential limitations in this dataset and that significant additional technical publications may not be included in the WOS Science Citation Index-Expanded; thus there may be underreporting of publications stemming from ARPA-E funded research using this source.

To determine whether a publication was highly cited, additional information was downloaded from Thomson Reuters to supplement the publication analysis: (1) a list of all indexed journals assigned to one of 22 categories, (2) citation thresholds for highly cited papers in each category by publication year, (3) a list of top journals with the number of highly cited papers published in that journal since 2005, and (4) a list of 88 journals classified by the Science Citation Index subject category "Energy and Fuels."

In the paper-level dataset, 9 percent of papers were in journals classified under Energy and Fuels, 23 percent were in a top journal, and 5 percent were highly cited for a given field and year. The most prevalent journal categories were Chemistry, Physics, Engineering, and Materials Science; 71 percent of the papers were in one of these four categories.

USPTO maintains a publicly accessible website with the full text of all patents issued since 1976, which was used to determine the patenting activity associated with DOE awards. All searches of the USPTO site were automated using an HTML web scraper. For each award in the DOE dataset, the consultant searched for the award number in the Government Interest field of all USPTO records and then extracted the patent title, patent number, date, and number of claims from the web page of all patents granted through December 31, 2015, that acknowledge an award in the DOE dataset. Separate searches also were conducted to obtain citations made to each of these patents through December 31, 2015. The patenting outputs associated with each award were added to the DOE dataset.

A patent-level dataset also was created on the basis of distinct patents that acknowledge an award in the DOE dataset. Patent databases often lack identifying contract information in the government interest section, so the patent count may also be underrepresented here (Jaffe and Lerner, 2001). There were 392 patents in this set, 2 of which jointly acknowledged two DOE offices. An ARPA-E award was acknowledged by 75 patents.

Separately from the DOE data that were downloaded from USAspending.gov, ARPA-E provided the committee with data on its award history, which were current as of September 17, 2015. These data were organized by project and included project characteristics specific to ARPA-E, such as which technology program funded the project. As discussed in Chapter 2, programs that are broadly solicited across all technology areas are considered "open"; there have been three such programs in ARPA-E—OPEN 2009, OPEN 2012, and OPEN 2015.

Data on organization type of awardees provided by ARPA-E were supplemented with company founding year, which was obtained from public data sources (e.g., state government registries). Awardee companies were categorized as start-ups if they had been founded 5 years or less before the start of the project, while all other business awardees were categorized as established companies. Additionally, the partnering organizations listed on each project were coded as universities, private entities (for-profit and nonprofit), or government affiliates (including national laboratories and other state/federal agencies).

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Two steps were taken to narrow the scope of ARPA-E awards considered in this analysis, both of which made the ARPA-E dataset similar to the DOE dataset:

- Projects with an end date on or before September 30, 2015, were removed.
- Projects led by national laboratories were also removed.

Excluding active projects allowed a fair comparison among those projects that had completed their negotiated R&D activities. The early outputs from ongoing projects, some of which had just begun at the end of FY 2015, would not have accurately represented the productivity of these projects. This step had a dramatic effect on the size of the dataset—more than half of the projects initiated by ARPA-E as of September 30, 2015, were still active at that time. Projects led by national laboratories are funded by ARPA-E through work authorizations under the management and operations contract between DOE and the laboratory. Many of these projects are in fact subprojects of a parent project led by a different organization. In these cases, it is likely that the outputs of a project will acknowledge the award number of the parent project, rather than the national laboratory contract itself. As a result, it was not possible to assess accurately the output of the projects led by the laboratories individually.

The resulting dataset ("ARPA-E dataset") contained 208 awards. It is important to note that the observations in the ARPA-E dataset are only a subset of the 263 ARPA-E awards in the DOE dataset because ARPA-E reports data on a per-project basis, and each project may encompass multiple awards (e.g., one to the lead awardee and one to each partner). Another consequence of this difference in award-based versus project-based accounting is that awards may have different start and end dates according to the two different data sources. For both the ARPA-E and DOE datasets, the consultant used the stated start and end dates from each data source to determine project duration and the fiscal year in which the project began.

In addition to the patent and publication data described above, the ARPA-E dataset contained information on additional metrics on "market engagement," as defined by ARPA-E. In a public press release on February 26, 2016, the agency provided lists of projects that had achieved the following outputs: formation of a new company, private investment, government partnership, IPO, and acquisition (ARPA-E, 2016). These metrics were used as early indicators of market engagement. The consultant analyzed both the likelihood of producing at least one output (patents, publications, or market engagement), and assessed the incidence rate for producing a number of outputs. The consultant also controlled for award amount and project length.

SUMMARY

This appendix has provided details of the committee's framing of its task as well as specific methods used in this assessment. This discussion is intended to help the reader understand the operational and technical assessments that appear in Chapters 3 and 4, respectively. In particular, the committee used its individual interviews, observations of ARPA-E events, and quantitative analysis of internal data in the operational assessment described in Chapter 3. The committee used its case studies and quantitative analysis of external data in the technology assessment described in Chapter 4.

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Appendix C

Case Studies Used to Assess ARPA-E's Operations and Potential to Achieve Energy Impacts

Case studies were one of the methods used by the committee to assess ARPA-E's operations and its progress toward achieving its statutory mission and goals. This appendix presents the findings from the case studies; the approach used in conducting the case studies is described in Appendix B. The case studies focus on the role ARPA-E played in managing these projects and programs and the committee's assessment of the potential transformative nature of the technology, the impact on the field, and expectations for market adoption. The committee is aware of the limitations of using case studies to draw overarching conclusions about ARPA-E—in particular, that these case studies are not representative of all agency programs and projects. As described in Appendix B, the case studies were just one of the methods used for the committee's assessment of the agency. Each case study was reviewed and approved by the respective performers.

An important consideration when attempting to evaluate the success of the programs and projects described in the case studies was the state of maturity of ARPA-E. As emphasized throughout this report, at the beginning of the committee's assessment, ARPA-E had been in operation for 6 years, a relatively brief time. Because most agency projects are funded for approximately 3 years, there were roughly 3 years' worth of complete projects to examine for this assessment. Therefore, the focus was on evaluating ARPA-E's operations and providing a technical assessment of whether the selected programs and projects met ARPA-E criteria of funding potentially transformative or white space technologies not already being funded by industry or other funding agencies because of technical and financial uncertainty.

Three types of case studies are presented in this appendix. The first focuses on a single program—Strategies for Wide-bandgap, Inexpensive Transistors for Controlling High-Efficiency Systems (SWITCHES); the second on a portfolio of electricity storage projects; and the third on 10 individual cases studies grouped into three categories—successful, cancelled, and other projects.

ONE PROGRAM: SWITCHES

To understand the implementation of and impacts from a broad set of projects, the committee undertook a case study of a single program—SWITCHES—and the broad set of projects on electric battery storage described in the next section. In both instances, the committee

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purposely selected cases with the potential for a broad set of impacts. The following description of the SWITCHES program highlights many of the hallmarks of ARPA-E, including program director autonomy; investments in high-risk technology; and plans for ensuring commercialization pathways, including the need to keep manufacturing of power electronics in the United States.

Program Description

Power electronics are ubiquitous and key to modern life and infrastructure. Vast efforts go into making electronic switching work better. Specifically, this means developing devices that are more efficient, longer-lasting, lower-cost, and useful in new applications. For example, improvements in power electronics can make the grid more efficient and reliable and improve integration of renewables, with known benefits from these capabilities amounting to many billions of dollars per year. Less clear but also compelling are the possibilities for improvements in power electronics to lead to completely different strategies for electric vehicles or lighting whose impact may be much greater if realized in conjunction with other innovations. The power electronics toolkit used by the industry is focused on well-understood and proven materials. The SWITCHES program sought proposals for using less well-understood materials with the potential to be tens or hundreds of times better for some vital applications, but not being pursued because the risks of failure were too high and time to market was too long. Specifically, the program is funding transformational advances in wide-bandgap (WBG) materials, device fabrication, and device architectures to develop new types of semiconductors. The outcomes of the program have involved many paths that will lead not to products (as expected and intended) but to several highly promising performance records and prototypes than now can be considered worth developing alongside more traditional approaches.

Technology Overview

The objective of this program is not only to reduce the barriers to ubiquitous deployment of low-loss WBG power semiconductors but also to develop approaches that will bring the costs of these devices to functional parity with those of silicon transistors while offering better performance. The program encompasses four major tasks: (1) creating crack-free device substrates using an economically promising method, (2) growing a doped semiconductor layer on these substrates with necessary electronic properties, (3) demonstrating working electronic devices with increasing levels of voltage capability using these new materials, and (4) completing a technology-to-market (T2M) plan. Based on the price of existing high-voltage silicon power semiconductor devices (shown in Figure C-1), ARPA-E considered WBG devices achieving costs of below $0.10/A for a 1,200 V, 100 A device to be a primary technical target (ARPA-E, 2013a). Further, the agency considered the SWITCHES program to be a complement to the New Generation Power Electronics Innovation Institute, which is working to help create and manufacture WBG semiconductor-based power electronics in the United States (ARPA-E, 2014; DOE, 2014).

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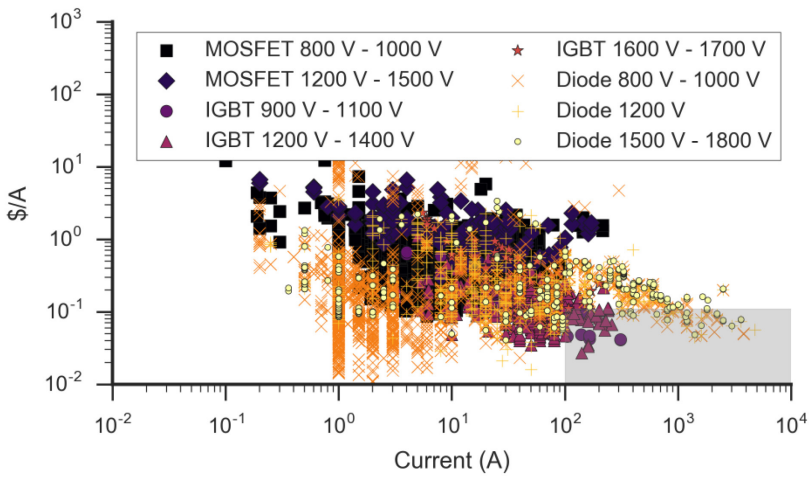

FIGURE C-1 Price of existing high-voltage silicon power semiconductor devices, based on data from the electronic components distributor Digi-Key. The gray shaded region was the target for the SWITCHES program.
NOTE: IGBT = insulated-gate bipolar transistor; MOSFET = metal-oxide-semiconductor field-effect transistor.
SOURCE: ARPA-E, 2013a.

Table C-1 lists the companies and projects in the SWITCHES program. Within the program, ARPA-E has funded 14 projects: 2 on diamond, 1 on silicon carbide (SiC), and 11 on gallium nitride (GaN). The emphasis is clearly on GaN. ARPA-E's focus in this program is to fund work designed to reduce the real and perceived risks of using nonstandard materials in power electronics switching. The scope of the work is intended to bring to practice complete devices (working prototypes) that can

- show that the new architecture, manufacturing technique, and/or materials set is feasible;
- demonstrate the well-known theoretical potential of these materials to set records in the key enabling metrics of the field (i.e., voltage, current density, switching frequency); and
- establish partnerships among materials scientists, device architects, technology companies, and original equipment managers to improve the chances that the work will be both relevant and perceived as such by eventual commercial adopters.

Roughly half of the funded projects are related to transistor technology and design, and roughly half to the synthesis of better substrate materials on which to build the transistor technology. This is a good mix that underscores the importance of materials issues in the development of the technology. The topics for the materials projects are well chosen and represent a balanced mix of bulk boule (single-crystal ingot)–based material and lift-off/spalling/thin film–based approaches. It is too early to tell whether the right ideas and principal investigators have been chosen. Nonetheless, the program directors have not hesitated to terminate projects when it makes sense to do so—2 of the 14 projects were cancelled within 2 years, actions that represent a robust and active oversight policy.

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TABLE C-1 Projects Funded under the SWITCHES Program

Project	PI and Lead	Collaborators	Description	Remarks	Years
P Doped Diamond Power Transistors	ASU		Diamond, vertical devices	Use innovative diamond growth approach	2014–2016
Vertical GaN Transistors on Bulk GaN	Avogy	ABB, NCSU, ORNL, Soraa	Vertical devices	30 times smaller transistor than Si, cost parity with Si in 3 years	2014–2017
Vertical GaN Power Transistors on Spalled GaN Layers	Columbia	IBM, IQE, MIT, Veeco	Vertical devices	Spalled GaN layers from bulk GaN that are transferred to Si	2014–2017
Polar JFET	Cornell	IQE, Triquint, United Tech.	Vertical devices		2015–2017
GaN Single Crystal Substrates	Fairfield crystal	Stony Brook	Bulk GaN	Use unique boule growth	2014–2015
Vertical GaN Transistor	HRL	Kyma, Malibu, Virginia Tech	Vertical devices	Develop a vertical GaN transistor process	2014–2017
GaN on Flexible Metal Tape	iBeam materials	Los Alamos and Sandia National Laboratories	Thin-film GaN	Develop GaN thin films using ion beam alignment on metal tapes using superconductor film technology	2014–2016
Transformational GaN Substrate Technology	Kyma	Avogy, Soraa, White Light, PSU	Bulk GaN	Convert seeds to boules using HVPE	2014–2018
Diamond Diode and Transistors	Michigan State	Fraunhofer	Diamond	Diamond—better way of doping diamond and making devices with doped components	2014–2016

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Vertical Junction FETs on Epitaxial Liftoff Substrates	Micro Link	Ammono, ND, VPI, Triquint	Vertical junc. FETs	Use epitaxial lift-off techniques to reuse GaN substrates	2014–2017
Advanced Manufacturing and Performance Enhancements for Reduced Cost SiC Devices	Monolith	RPI	SiC	Use existing SiC manufacturing facilities, but design efficient process flows and device designs to make more efficient/cheaper high-power SiC transistors	2014–2016
HVPE of GaN on GaN Wafers—Homoepitaxy	Six Point	Cornell, ND	GaN substrates	Will do HVPE on bulk GaN	2014–2017
High-quality GaN Substrates	Soraa		GaN substrates	GaN substrates growth in ammonothermal reactor	2014–2015
Current Aperture Vertical GaN Transistor	UCSB	Transphorm, U.S. Naval Research Laboratory	GaN vertical transistor	Development of compact transistors	2014–2017

NOTE: ASU = Arizona State University; FET = field effect transistor; GaN = gallium nitrate; HVPE = hydride vapor phase epitaxy; JFET = junction field effect transistor; MIT = Massachusetts Institute of Technology; NCSU = North Carolina State University; ND = Notre Dame; P = phosphorus; ORNL = Oak Ridge National Laboratory; PI = principal investigator; PSU = Pennsylvania State University; Si = silicon; SiC = silicon carbide; UCSB = University of California, Santa Barbara; VPI = Virginia Polytechnic Institute.

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Technology-to-Market Prospects

Power electronics are projected to play an increasing role in the delivery of electricity, with as much as 80 percent of electricity passing through power electronics devices between generation and consumption by 2030 (Tolbert et al., 2005). These devices are used in the control and conversion of electricity. At one end of the spectrum, they can involve the use of transistor devices that switch circuits operating at high power, with currents of approximately 100 A or higher and voltages of approximately a few hundred to a few thousand volts, and high temperatures (100–700 °C). Such circuits are increasingly desirable in such applications as electric power generation and distribution circuitry (e.g., inverters), automotive electronics, and motor drives. This is in contrast with transistors that are used in microprocessors for computing, where the currents are in the micro-amp range, and the voltages are less than 1 V.

Within the SWITCHES program, ARPA-E recognized the substantial potential for WBG semiconductor materials to provide energy savings and new designs for these applications over current technologies. The agency sought to fund transformational advances in WBG materials, device fabrication, and device architectures. The goal of this program was to enable the development of high-voltage (approximately 200–2,000 V), high-current power semiconductor devices and circuits that, upon ultimately reaching scale, would have the potential to offer affordable breakthrough performance in terms of low losses, high switching frequencies (and therefore smaller packages), and high-voltage operation (ARPA-E, 2013a). Currently, industrial power electronics circuits are overwhelmingly (>95 percent) built with transistors made out of silicon. Silicon power transistors, however, become increasingly inefficient beyond operating voltages of 400–500 V. There is demand today for power transistors that operate in the approximately 650 V range for circuits that can be plugged into the wall. A second set of needs is in the 1.2–1.7 kV range for automotive applications. The adoption of WGB semiconductors is a move toward higher-frequency circuits, which allow decreased component sizes and increased efficiencies. Figure C-2 shows the improvements afforded by various WBG semiconductors over conventional silicon.

Overall, the move to low-loss WBG power semiconductor devices would enable enhanced efficiency of electric motors through improvements to variable-frequency drives; substantially reduce the weight and additional cost of power electronic systems for plug-in electric vehicles; and reduce the cost, weight, and volume of and losses from wind and solar electric power inverters. There would be other potential applications as well. Engineers do not wait for innovations from the science world before designing things. The corollary is that, once scientific discoveries have been brought into the design space, engineers will find applications not fully conceived of today. Thus, ARPA-E's efforts in the SWITCHES program are consistent with its goal of bringing potentially transformational technologies beyond discovery into the demonstration phase.

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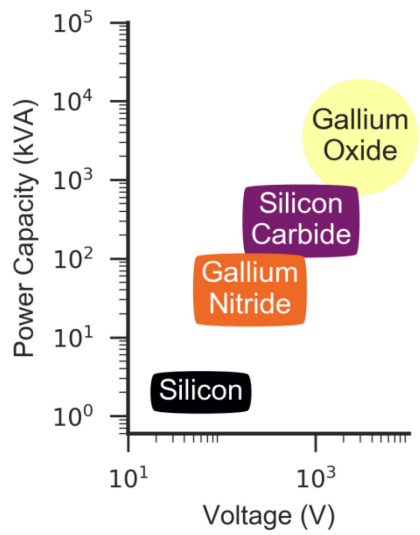

FIGURE C-2 Relationship between performance dimensions of power capacity and voltage for representative semiconductors and gallium oxide (Ga_2O_3).
SOURCE: NICT, 2012.

The power electronics market has been growing at about 10 percent per year, which is considered relatively high for the semiconductor industry. New power transistors and circuits that satisfy the above needs will introduce a disruptive change in this field. A few new semiconducting materials that have wider band gaps than silicon, are more refractory (i.e., stable at high temperatures) in nature, and have higher electric breakdown fields are being explored actively for these power transistor applications. Among these WBG materials, GaN and SiC are the top two candidates. GaN is targeted for 650 V operation and for higher-frequency operation at lower temperatures because of its higher carrier mobilities and efficiencies. SiC's sweet spot is greater than 1 kV, and work is ongoing on increasing its attractiveness for lower voltages. Other less-developed but promising materials are diamond, gallium oxide (Ga_2O_3), and aluminum nitride (AlN).

Role of ARPA-E Program Director

The ultimate responsibility for a program like SWITCHES lies with its program director. The full team monitoring and supervising projects consists of a front office team and a back office team. The former, which includes the program director, contractors with technical expertise that are hired to augment the program director, and T2M staff, is responsible for quarterly reviews, contractor site visits, and annual reporting. The back office team is responsible for maintaining administrative, legal, and financial precision. This arrangement appears to provide an appropriate mix of project rigor and project leadership discretion. For the SWITCHES program, this means that goals, schedules, and expectations have been stated clearly from the outset, and each project is subject to 10 or more "touches" per year by the front office team, including quarterly reviews, annual reviews, teleconferences, site visits, and other events. "Pivots," or changes in milestones, are rigorously documented and tracked. In general, the committee observed that the program directors and the core staff are highly competent, dedicated, and responsive.

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The committee noted that Tim Heidel, program director for SWITCHES, has been active in presenting the SWITCHES program, both in the peer-reviewed literature (Heidel and Gradzki, 2014) and at seminars and conferences (Heidel, 2014; Heidel et al., 2015). The committee's case studies include two projects for which Dr. Heidel served as program director—the Low-Cost Gallium Nitride Vertical Transistor project in the SWITCHES program and the Distributed Power Flow Control project in the Green Electricity Network Integration (GENI) program. The performers for these projects highlight that Dr. Heidel and his team have scoped, shaped, and supported their projects productively and efficiently.

Committee Assessment

The SWITCHES program clearly aspires to have a transformational impact on power semiconductor devices. As described in the Funding Opportunity Announcement (FOA), the potential energy-efficiency gains from WBG materials in the areas of motor drives, automatable applications, and electric power generation are substantial. More fundamentally, if the boundaries on switching frequency, voltage, and temperature can be significantly moved, the design space changes. Some devices can become cheaper, smaller, and more efficient, but more important, some applications that were otherwise impossible will become feasible. It is likely that, moreover, the near-term applications of improved switches using WBG semiconductors greatly understate their impact because many of the systems that will utilize these devices have not yet been conceived. The impact of changing the engineering toolkit for all electrical systems is large but also difficult to predict. The development of disruptive power electronics technologies from these emerging WBG materials is a timely and worthwhile objective that has the potential to enable significant technology advancements.

The combination of potential impact and risk associated with launching a new materials set for power electronics is high. The default material choice is always silicon because it is cheap and has established supply chains. The risk is that the WBG devices could be a decade away from invention to profit, let alone broad application, and the tooling is costly. So the largest producers of power electronics are likely to continue using the silicon devices that are supplied by the foundries with which they have established relationships. Only if the producers are confronted with the real likelihood that someone can beat the performance of the incumbent devices by a significant margin will they consider making the significant investments required to change materials sets. The case of GaN blue and green light-emitting diodes, introduced by Nichia, a new entrant to this space in the early 1990s, is just such an example of a new technology shaking up entrenched manufacturers.

The committee's assessment is that the overall project participant mix within the SWITCHES program has been good in terms of mixing materials, devices, and university and industry skills. However, the absence of most of the major industry players (with the possible exception of Triquint) on the list of funded power electronics projects is significant. It represents a lack of suitable "catchers" should the technology be successful, a risk profile that may be somewhat extreme, and a T2M strategy (specific to semiconductor technology) that may require some refinement. Some of the notable manufacturers, leading technology providers, and new entrants to the area of high-power electronics technologies are Infineon (which recently acquired a major player, International Rectifiers), Panasonic, Cree, Rohm, Texas Instruments, ST Micro, Transphorm, TSMC, On-Semi, NXP, and EPC. Other than Transphorm, none of these companies appears to be participating formally in the ARPA-E SWITCHES projects.

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The path to developing a semiconductor technology can be complicated. At the end of a typical 3-year project cycle, a good technical concept that has undergone a well-executed development process will lead to a promising technology—typically one for which most of the risk elements entailed in feasibility and scalability demonstration have been eliminated. The path from there to a manufacturable product with satisfactory cost, yield, and performance is one that requires sustained additional funding over a period of an additional 2–5 years. In the instance of silicon technology for microprocessors, large companies such as IBM, Intel, and Samsung have accomplished this either through internal funding (Intel) or through consortia or alliances in which the investment and risk are shared (IBM and Samsung). In the case of WBG power electronics, this path lacks clarity: most of the companies involved are not large enough (except for companies such as Infineon) to sustain this type of technology development. The 3-year timeframe for these projects has started the research and development (R&D) process, but more research is required to evaluate the promise of semiconductor technology in power electronics.

As noted earlier, ARPA-E is coordinating with the U.S. Department of Energy's (DOE) New Generation Power Electronics Innovation Institute, which is working to help create and manufacture WBG semiconductor-based power electronics in the United States. Further, while ARPA-E has not provided funding to move a technology from prototype to scalable product to date, the agency's most recent budget request included a proposal for an "ARPA-E Trust" to address scale-up and system-level challenges. Given where WBG semiconductors are on their development pathway, they may be a good target for such funding.

ONE PORTFOLIO: ELECTRICITY STORAGE

Portfolio Description

ARPA-E funds its electricity storage (primarily electric battery) projects through the Batteries for Electrical Energy Storage in Transportation (BEEST), Grid-scale Rampable Intermittent Dispatchable Storage (GRIDS), and Robust Affordable Next Generation Energy storage systems (RANGE) programs, as well as through its OPEN 2009, 2012, and 2015 solicitations. The projects in the GRIDS program, which began in 2010, focused on developing technologies that can store renewable energy for use at any location on the grid at an investment cost below $100 per kilowatt hour (kWh). The projects in the BEEST program, which began in 2011, focused on developing a variety of rechargeable battery technologies for plug-in electric vehicles to meet or beat the price and performance of gasoline-powered cars. The program considered radical improvement of current lithium-ion technologies and new designs using other battery chemistries that incorporate magnesium, sodium, zinc, lithium-sulfur, and lithium-air designs. The projects in the RANGE program, which began in 2013, continued efforts to develop rechargeable battery technologies for plug-in electric vehicles (focusing on battery designs that would enhance safety), to maximize the overall energy stored in a vehicle, and to minimize manufacturing costs. The OPEN 2009, 2012, and 2015 solicitations were designed to fund transformational breakthroughs across the entire spectrum of energy technologies, including stationary and transportation electricity storage projects. A number of storage projects were funded by the OPEN 2015 call; as these are very new projects, however, the committee did not include them in any of the analyses provided below.

Electricity storage at ARPA-E represents approximately 10–15 percent of all projects funded by the agency, making this thrust area clearly one of the largest classes of technologies

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funded through the past 6 years. The committee therefore performed a high-level assessment of the ARPA-E electricity storage technology portfolio to examine how, at least for this field, the agency has had impact and whether any broader trends within this group of projects may reflect the strengths and weaknesses of its approaches. It should be noted, however, that the extent to which this collection of projects can be thought of as a true portfolio is unknown—specifically, the extent to which the agency considers prior electricity storage funding decisions and technical content in weighing the relative programmatic merits of new proposals, especially for those storage projects awarded in the OPEN calls.

The purpose of this exercise was to examine numerically all of the electricity storage–themed projects that ARPA-E funded from its inception through 2014. The goals were to

- provide additional analysis for the case study effort to show how a single class of technologies (electricity storage) within ARPA-E functioned;
- search for patterns or trends;
- examine whether the narrative ARPA-E portrays is reflected in reality;
- compare data from the storage field with the quantitative analyses applied to all ARPA-E projects; and
- provide the committee's other working groups with additional data.

For this analysis, the committee looked only at electricity, not thermal storage projects. Additionally, the committee did not consider programs or projects designed to explore improvements to battery management systems, sensors, or testing. The data, descriptions, and other information on these projects used in this section were obtained from the ARPA-E projects website.[1]

Project Funding Characteristics

As shown in Figure C-3, ARPA-E funded 63 electricity storage projects through 2014; 5 have been cancelled, 30 are still active, and 28 have been completed. This record can be compared with ARPA-E's overall project funding: according to the agency's website,[2] a total of 484 projects have been funded, 25 have been cancelled, 249 are still active, and 210 have been completed. Thus, the cancellation rate of electricity storage projects (8 percent) is somewhat higher than that of ARPA-E's projects in general (5 percent). While storage projects may be inherently risker than other types of projects, the committee noted no obvious patterns or similarities among the cancelled projects.

[1]https://arpa-e.energy.gov/?q=arpa-e-site-page/projects (accessed April 26, 2017).
[2]ARPA-E's website is http://arpa-e.energy.gov/?q=arpa-e-site-page/projects (accessed August 8, 2016).

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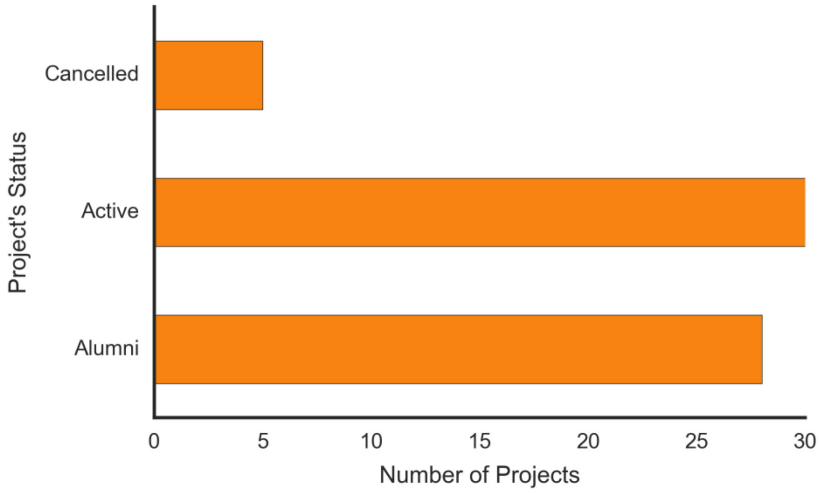

FIGURE C-3 Electricity storage projects by status, 2009–2014.

Table C-2 shows the funding for the electricity storage projects. ARPA-E spent a total of just over $170 million and garnered $65 million of cost-share contribution for electricity storage projects in the timeframe analyzed. This level of funding rivals that provided by DOE for storage efforts in the same timeframe, even when the founding of the Joint Center for Energy Storage Research (JCESR) at Argonne National Laboratory is included.

TABLE C-2 Funding for Electricity Storage Projects, 2009–2014

Total ARPA-E Funding	$170,738,843
Total Cost Share	$64,422,468
Total Funding	$235,161,311

Program Name	# of Awards	ARPA-E Funding	Cost Share	Total Funding	Average Per Project
BEEST	10	$32,412,615	$30,575,785	$62,988,400	$6,298,840
GRIDS	12	$32,024,077	$9,846,758	$41,870,835	$3,489,236
RANGE	22	$37,798,378	$7,368,717	$45,167,095	$2,053,050
OPEN 2009	7	$36,147,260	$9,662,382	$45,809,642	$6,544,235
OPEN 2012	12	$30,334,536	$6,430,369	$36,764,905	$3,063,742

	ARPA-E Funding	Cost Share	Total Funding	Duration (Years)	ARPA-E Funds Per Year	Cost Share Per Year	Total Funds Per Year
Average	$2,710,140	$1,022,579	$3,732,719	2.69	$980,820	$374,452	$1,355,273
Median	$2,520,428	$679,493	$3,256,862	2.99	$880,037	$238,325	$1,132,487
Std. Dev.	$1,862,401	$1,805,664	$3,127,140	1.10	$525,937	$655,129	$1,009,666
High	$10,200,000	$12,987,613	$17,987,613	7.05	$2,844,751	$4,329,204	$5,995,871
Low	$450,001	$25,000	$500,002	0.55	$262,528	$15,090	$291,698

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The ARPA-E funds were distributed approximately equally among the five different programs that sponsored electricity storage projects considered here (RANGE, BEEST, GRIDS, and OPEN 2009 and 2012), although the programs that funded more individual projects, in particular the RANGE program, received lower per-project funding. The typical electricity storage project lasted 2.7 years and consumed approximately $980,000 per year of ARPA-E funding; however, funding levels and durations varied by project. For example, the longest project stretched just over 6 years, and the most expensive project received more than $10 million in funds.

Focus Areas and Project Types

From a technology maturity perspective, the electricity storage projects were divided between proof-of-concept and prototyping and were shared between the stationary and transportation application spaces (Figure C-4). A healthy fraction of the projects (17/63) were "crossover" in nature in that the technology was intended to address both the stationary and transportation markets if successful. Importantly, no project focused its activities on scaling the production level of materials or devices, which would be expected given ARPA-E's explicit emphasis on early-stage R&D and device proof-of-concept.

As noted above in the description of the SWITCHES program, ARPA-E's most recent budget proposal included a request for $150 million for an "ARPA-E Trust" that would address scale-up and system-level challenges. The committee notes that the Defense Advanced Research Projects Agency (DARPA) already has this capability. Moreover, the long timeline and large capital requirements for scaling up new battery technologies mean that such longer-term funding streams may be appropriate for especially promising electricity storage projects.

The committee reviewed the project descriptions and classified the projects based on their technical focus (Figure C-5). Of interest, the focus of these projects was not solely technical; some were focused mainly on safety, and others on durability. Not surprisingly, the majority of the projects were at least partially cost-focused, while 6 had technology cost as a singular focus.

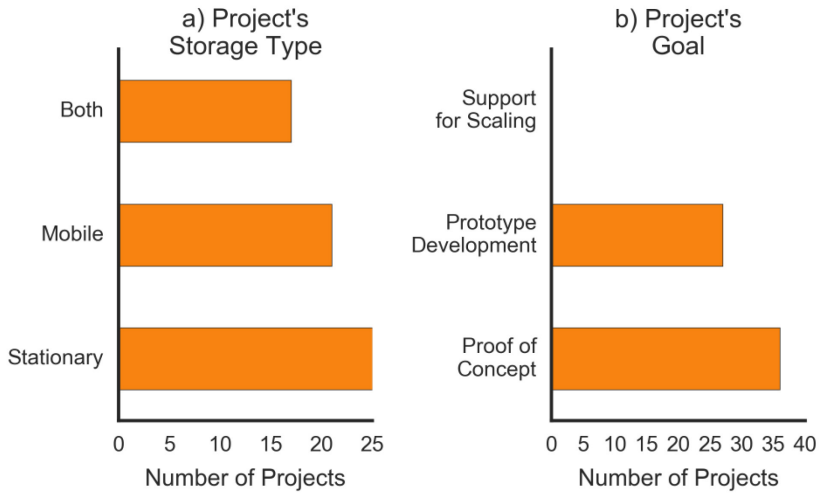

FIGURE C-4 Type of storage project (a) and technology maturity goal (b), ARPA-E electricity storage projects funded 2009–2014.

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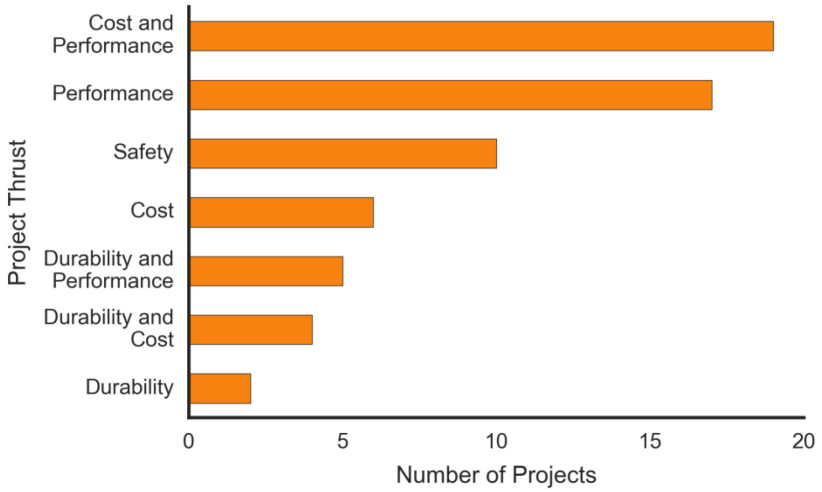

FIGURE C-5 Focus of the ARPA-E electricity storage projects funded from 2009 to 2014.

Project Principal Investigators and Collaborators

The committee reviewed the expertise of the principal investigators who were funded for storage projects. This review included whether the principal investigator had previous research published in the literature, patents, or industry experience related to storage technologies. In approximately 90 percent of the projects, the principal investigator had demonstrated a strong background in the key required technical fields, indicating that in most cases, the principal investigators for the funded projects were established in the necessary fields.[3]

The committee also looked at the primary affiliations of the principal investigators and project collaborators, as well as the profiles of the collaborations. University and small company principal investigators were dominant awardees, and a diverse range of collaborator combinations was observed. Figure C-6 shows that there was no dominant combination of principal investigators/co-principal investigators, although there were no instances in which project participants consisted of only national laboratory performers, as mandated by the ARPA-E funding rules. Notably, there was only one case in which the project had only university team members. The extent to which this collaboration profile reflects the applicant pool and whether certain types of collaborations were emphasized are unclear.

[3]This analysis did not consider the backgrounds of the co-principal investigators and other project collaborators.

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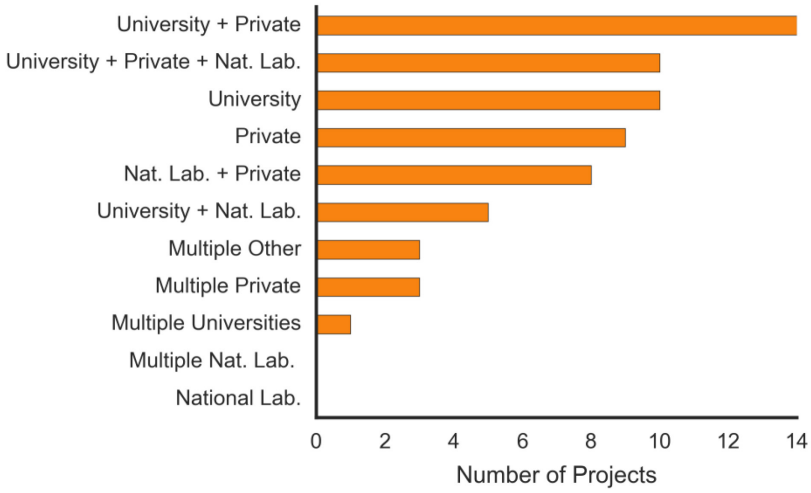

FIGURE C-6 Performer collaboration types of electricity storage projects funded by ARPA-E, 2009–2014.

Outcomes and Role of ARPA-E Program Directors

The committee compiled three metrics of impacts—publications, patents, and follow-on funding—for the electricity storage projects, shown in Table C-3. These projects had produced a total of 115 peer-reviewed papers and 22 patents as of January 2016. Of the published papers, 37 appeared in high-impact journals, and 5 were highly cited, while a total of 20 companies (approximately 30 percent) received follow-on funding from public and/or private entities. As of the end of 2015, 4 companies had a manufactured product on the market that had been developed during or after the receipt of ARPA-E funding. However, it is not completely clear that all these products were the same as those developed with ARPA-E support.

The committee also looked at how the outcomes from the electricity storage portfolio compared with those of the entire collection of projects funded by ARPA-E. Company formation has occurred with 7.5 percent of ARPA-E-funded projects, compared with 9.5 percent of the electricity storage projects; the corresponding figures for follow-on funding are 9.5 percent for all of ARPA-E versus 19 percent for the electricity storage projects. Thus it appears that the electricity storage portfolio has produced similar or slightly better outcomes in terms of funding and technical development relative to all ARPA-E projects.

TABLE C-3 Impact Analysis of the 63 Electricity Storage Projects Funded by ARPA-E from 2009 to 2014

Total publications	115
Publications in high-impact journals	37
Number of highly cited papers	5
Total number of patents	22
Number of companies formed	6
Number of projects receiving follow-on funding	20
Number of projects receiving private funding	12
Number of projects receiving subsequent public funding	14
Number of companies with a product in the market in 2015	4

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In total, there have been 15 different program directors for these electricity storage projects, and in nearly every case, the projects were transferred to new directors. This is because the typical tenure of ARPA-E program directors is approximately the same as the average project length, and as described earlier in this report, it typically takes program directors at least 9 months after joining the agency before a program for them to direct is initiated. Most of the program directors had the appropriate technical background for their projects, as well as significant experience in the entrepreneurial space.

Committee Assessment

ARPA-E was mandated to pursue and fund transformational ideas and to find technical white space lacking significant prior work. For about half of the electricity storage projects, there is clear evidence of technical white space being addressed (Figure C-7); that is, the project was using novel or underexplored approaches to address electricity storage problems. Further, while there is evidence of significant prior work in the public domain for 50 of the 63 projects, in half of these cases (25/50), this was work demonstrated at the principal investigator's institution.

The committee also looked at the storyline of the projects, meaning the combination of the type of project lead and type of project. Of the 63 electricity storage projects, 47 fall into the category of either "small company principal investigator further developing a novel technology" or "university professor principal investigator gaining support for a new idea." Additionally, 6 awards went to large companies exploring new concepts.

These data suggest that ARPA-E is doing a reasonable job of funding relatively novel projects in electricity storage that do not overlap significantly with work done elsewhere. Demonstration-style projects require prior work as a base, so it is not surprising that for just over half of the projects, there is significant evidence of prior similar work being conducted at either the principal investigator's or another institution (Figure C-7).

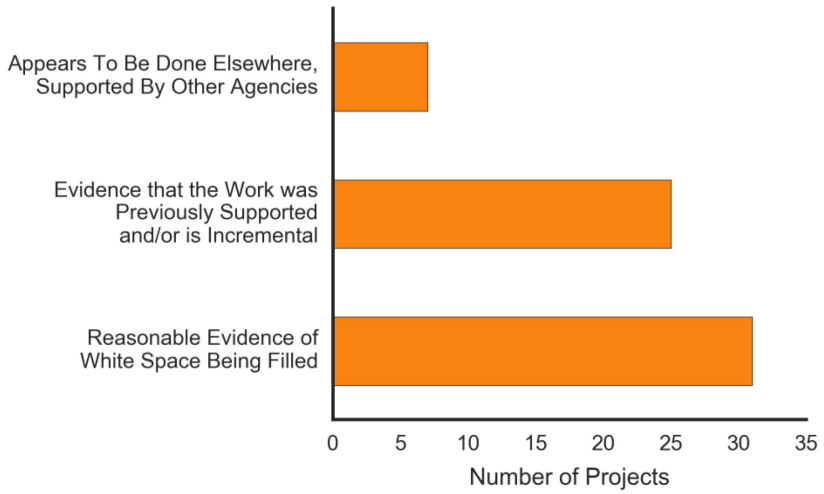

FIGURE C-7 Degree of novelty and prior support for ARPA-E electricity storage projects.

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Overall, the committee observed that ARPA-E has funded a wide array of projects related to electricity storage, and these generally have been projects that do not overlap significantly with work funded by other sources. Together with other efforts focused on thermal storage technologies (High Energy Advanced Thermal Storage [HEATS]), technologies for improving battery management and sensor systems (Advanced Management and Protection of Energy storage Devices [AMPED]), and approaches for testing and evaluating battery storage systems (Cycling Hardware to Analyze and Ready Grid-scale Electricity Storage [CHARGES]), the electricity storage projects reviewed here reveal that ARPA-E has invested a significant fraction of its resources in improving electricity storage systems. This is a worthy investment given the critical need for improved electricity storage in both the transportation and electricity sectors. The committee considers much of ARPA-E's electricity storage portfolio to have a medium or high degree of technical risk, meaning that these projects have goals that are beyond current technical capabilities and in many cases are difficult to achieve.

Given the high-risk/high-payoff approach that ARPA-E espouses in creating programs and funding projects, the degree of follow-on support from company founding for the electricity storage projects reviewed for this analysis appears to be reasonable, with a substantial portion of the funded projects finding significant support after the end of their ARPA-E funding. On the other hand, it can also be said that the majority of the companies that have actual electricity storage product offerings on the market today were funded by ARPA-E after being founded, and in most cases had a well-defined technical path forward. In these cases, the most common scenario is one in which ARPA-E funded either demonstration projects or product improvements. These types of demonstrations of and improvements to more mature concepts tend to make up the bulk of the projects that ARPA-E currently counts as successes, which is not surprising given that it takes 7–10 years to mature a new concept that would not have existed substantially prior to funding. Thus it is quite possible that more of those projects that have received follow-on funding could yield product offerings in the next 5 years.

INDIVIDUAL PROJECTS

As noted earlier, the committee's 10 individual project case studies are grouped in three categories: successes, cancelled, and other (Table C-4). These categories are defined as follows:

- Successes are projects that the committee or the agency considers likely to have or that have had market success in the energy sector and that have received follow-on private-sector funding.
- Cancelled are projects that were terminated before the original end date because they were not meeting their goals and appeared likely not to do so eventually.
- Other are projects that were completed and that to date have resulted in little or no direct energy market success, but still advanced the state of knowledge.

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TABLE C-4 ARPA-E Individual Project Case Studies

Company Name	Short Project Title	OPEN/Focused	Company Type
Successes—projects that the committee or the agency considers likely to have or that have had market success in the energy sector and that have received follow-on funding			
1366 Technologies	Cost-Effective Silicon Wafers for Solar Cells	OPEN 2009	Small Co.
24M	Semi-Solid Flowable Battery Electrodes	BEEST	Small Co.
Foro Energy	Laser-Mechanical Drilling for Geothermal Energy	OPEN 2009	Small Co.
Harvard University	Slippery Liquid-Infused Porous Surfaces (SLIPS)	OPEN 2012	Univ.
Smart Wires	Distributed Power Flow Control	GENI	Small Co.
Cancelled—projects that were ended before the original end date because they were not meeting their goals and appeared likely not to do so eventually			
General Electric	Nanostructured Scalable Thick-Film Magnetics	ADEPT	Large Co.
Other—projects that were completed and that to date have resulted in little or no direct energy market success, but still advanced the state of knowledge			
Agrivida	Engineering Enzymes in Energy Crops	OPEN 2009	Small Co.
Ceres, Inc.	Improving Biomass Yields	OPEN 2009	Small Co.
HRL Laboratories	Low-Cost Gallium Nitride Vertical Transistor	SWITCHES	Small Co.
Stanford University	Radiative Coolers for Rooftops and Cars	OPEN 2012	Univ.

NOTE: ADEPT = Agile Delivery of Electrical Power Technology; BEEST = Batteries for Electrical Energy Storage in Transportation; GENI = Green Electricity Network Integration; SWITCHES = Strategies for Wide-bandgap, Inexpensive Transistors for Controlling High-Efficiency Systems.

ARPA-E performers (principal investigators) for these individual case studies were asked about the state of their research before applying to ARPA-E, their reasons for responding to the agency's FOA, their interactions with their respective program directors and T2M teams, their methods for tracking progress against the metrics established for their projects, their accomplishments during the projects, and other observations about their projects that they wished to share. The case studies also include an expert assessment of the technology developed during each project and its potential to be transformational. Committee members provided the expert assessment.

It is important to note, as emphasized earlier, that these 10 case studies are not representative of all ARPA-E projects. In addition, it often takes many years for new technologies to be adopted by the market,[4] and thus this early assessment allows for the capture

[4]The Advanced Technology Program is similar to ARPA-E, so the commercialization timelines are expected to be similar. For successful technologies, the commercialization timing for information technology (IT) projects occurs primarily within 1 year after funding ends. Electronics technologies have some early applications, but then they experience a steep rise in activity in the second year after funding ends, followed by a fall-off more rapid than in any other technology area except IT. Materials-chemistry and manufacturing-based applications build up somewhat

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of only early outputs and outcomes (Powell and Moris, 2002). Nonetheless the technical assessments of these case studies provide insight into the potential for projects funded by ARPA-E to meet the agency's objectives of reducing energy imports; decreasing energy-related emissions, including greenhouse gases; improving energy efficiency in all economic sectors; and ensuring that the United States maintains a technological lead in the development and deployment of advanced energy technologies. The descriptions in this appendix focus on the role played by ARPA-E in managing these projects and the committee's assessment of the potentially transformative nature of the technology, the impact on the field, and expectations for market adoption.

Successful Projects

Five cases studies of projects defined as successful are described here (see Table C-4). It should be noted at the outset that, although these projects are categorized as successful in that they show potential for market introduction, none of them has as yet been transformational in the energy sector—as would be expected given the extended period of time in the market required for transformational technologies to become apparent. The five projects in this category include four led by small companies and one led by a university. Three were funded from OPEN FOAs and two from focused FOAs. A unifying characteristic of four of the five projects is that because they have recent and/or ongoing ties to university researchers, they are directly related to university research. In addition to the ARPA-E funding, agency program directors played a significant role in these projects. The performers acknowledged the benefits of the quarterly project meetings in keeping them on track, providing an opportunity to discuss and implement changes in research directions, and encouraging interactions with potential industry customers. Three of the five performers found the T2M team helpful, while the other two performers would like to have had more input on potential customers and funders. The five projects are as follows:

- 1366 Technologies is developing a process to reduce the cost of solar electricity by up to 50 percent by 2020—from $0.15 per kWh to less than $0.07 per KWh. 1366's wafers could directly replace wafers currently on the market, so there would be no interruptions in the delivery of these products to market. As a result of 1366's technology, the cost of silicon wafers could be reduced by 80 percent.
- Scientists at 24M are developing lithium (Li)-ion battery cells for electricity grid applications that have a higher energy density and are much simpler to manufacture than current state-of-the-art large-format Li-ion batteries.
- Foro Energy has developed a unique system for transmitting high-power laser light over long distances via fiber optic cables to ablate or weld materials. The company's laser-assisted drill bits have the potential to be up to 10 times more economical than conventional hard-rock drilling technologies, making them an effective way to access the U.S. energy resources currently locked under hard-rock formations. Foro Energy was created based on R&D developed during the previous decade at the Colorado School of Mines.

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more slowly and trail off more slowly than electronics and IT. Biotechnologies have an initial spurt of activity in the second year after funding ends but then have another spurt 5 or more years later.

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- Harvard University developed a slippery coating technology that can be used for a number of commercial applications, including oil and water pipelines, wastewater treatment systems, solar panels (to prevent dust accumulation), and refrigeration (to prevent ice buildup), as well as many other energy-relevant applications. The performer started a company called Slippery Coatings.
- Smart Wires developed a solution for controlling power flow within the electricity grid to better manage unused and overall transmission capacity. The technology has the potential to support greater use of renewable energy by providing more consistent control over how that energy is routed within the grid on a real-time basis. The project was based on research conducted at Georgia Tech.

Cost-Effective Silicon Wafers for Solar Cells (1366 Technologies)

Project description 1366 Technologies is developing a potentially disruptive solar technology, a process aimed at reducing the cost of solar wafer manufacturing by 50 percent by 2020. Silicon solar wafers are the building block of solar cells and panels, and reducing their costs would have dramatic implications for solar's adoption rate. Deployments of solar cells are increasing at double-digit annual growth rates (SEIA and GTM Research, 2016) because they are cheaper than ever, reliable, and clean. However, as costs come down on other parts of photovoltaic (PV) installation, manufacturing costs are constrained by wafer production, which accounts for 40 percent of the overall panel cost. These wafers have been made the same way for decades. Instead of growing expensive crystals and cutting them into thin fragile wafers, 1366 casts the wafers directly from molten silicon and can make shapes that are more durable and use less material. The efficiency of these cells compares favorably with that of today's advanced technologies, so 1366's wafers could seamlessly replace wafers currently used in the market while greatly reducing their costs. ARPA-E provided 1366 with funding to investigate the basic science that helped lead to a technology capable of being commercialized. Since most solar panels are made outside of the United States, 1366's technology and the company's development of solar wafer manufacturing facilities in this country could increase domestic PV production dramatically, thus increasing U.S. energy security (ARPA-E, 2016a).

Project funding characteristics 1366 Technologies was selected in the OPEN 2009 solicitation. This is one of the few projects funded by ARPA-E in solar and the only one on novel silicon production technologies. It was not part of a managed program and did not benefit from synergies with other programs. ARPA-E funded the project at $3,999,828 between March 2010 and June 2012 (Figure C-8).

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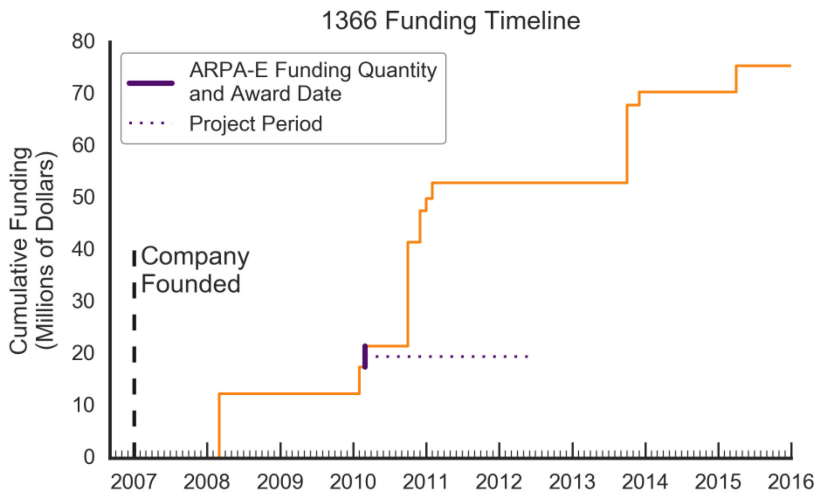

FIGURE C-8 Funding history for 1366 Technologies.
NOTES: The figure shows the timing and amounts of funding for the company's inception, for ARPA-E funding (purple), and for external funding from other sources (orange). 1366 Technologies received venture capital funding prior to ARPA-E funding; it received $4 million from March 1, 2010, to June 30, 2012; and it received more than $50 million of follow-on funding.
SOURCES: crunchbase.com, 1366tech.com, arpa-e.energy.gov, ARPA-E.

Technology overview 1366 Technologies has been consistent in its stated goals and has not wavered in its efforts to manufacture low-cost silicon PV cells. A spin-out of the Massachusetts Institute of Technology (MIT), 1366 Technologies built on the ideas of several U.S. companies that preceded it, including Mobil Tyco and General Electric (formally AstroPower). The combination of industrial experience and the talent from America's best technical universities led to the breakthrough insights that made 1366 possible. The company's direct wafer technology significantly reduces manufacturing costs by producing wafers directly from a melt rather than cutting ingots of crystallized silicon. 1366's process avoids the costly step of slicing a large block of silicon crystal into wafers, which turns half the silicon to dust. Instead, the company is producing wafers directly at industry-standard sizes and with efficiencies that compare favorably with those of today's state-of-the-art technologies. The company also has developed a few manufacturing techniques for incremental improvements in polycrystalline silicon PV efficiency by improving light harvesting through reduced reflectivity that results from texturing the surface and reflective substrates.

1366 has developed a potentially disruptive solar technology that benefited from ARPA-E funding. It is a successful example of the freedom to pursue basic science, turning a promising innovation into a technology that can be commercialized. Developing a new way to manufacture silicon cells is revolutionary, but while the technology is promising, success is not yet assured. The agency estimates that 1366's technology could reduce the cost of silicon wafers by 80 percent (ARPA-E, 2016a).

Technology-to-market prospects The technology developed by 1366 has the potential to reduce the cost of solar power significantly, making it cost-competitive with coal power in some parts of the United States within 10 years. This technology could help the United States capture a majority of the annual $10 billion silicon wafer market and motivate solar manufacturers to locate in the United States. Positioning solar energy production as a renewable, environmentally

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friendly, and cost-effective alternative to fossil fuel-based energy production would reduce the addition of carbon dioxide to the atmosphere by millions of tons.

Outcomes and ARPA-E's role 1366 Technologies currently operates a manufacturing site capable of throughput in excess of 15 megawatts (MW) of wafers per year, consisting of three parallel production lines each with one production furnace. This is a demonstration line that is the blueprint for the company's first commercial-scale facility, which will house 50 direct wafer furnaces. In October 2015, 1366 announced it will build a 250 MW commercial facility in Genesee County, New York. The facility will initially produce 50 million wafers each year and scale to 3 gigawatts (GW) of capacity, manufacturing 600 million wafers each year. 1366 is in a partnership with Hanwha Q Cells, which has also committed to purchasing 700 MW from the commercial facility during its first 5 years.

At the time of the ARPA-E solicitation, 1366 was a young company seeking funding. It was in the midst of a funding round and growth at the time of the ARPA-E award. ARPA-E funding represents a small fraction of the total capital 1366 has raised to date, but was approximately 20 percent of the total amount raised at the time of the grant. ARPA-E was credited in a press release stating, "The Company's rapid progress during the last year was triggered by a $4 million grant the company received from the Department of Energy's ARPA-E program in December of 2009" (1366 Technologies, 2010). Of the follow-on $50 million in funding, $23 million was foreign investment in the United States, creating U.S. jobs and generating U.S. tax revenue. Further, 1366 benefited from the positive press associated with videos and its presence at the ARPA-E Energy Innovation Summits.

The flexibility and autonomy of the program director allowed 1366 to demonstrate the wafer-making method that ultimately became the company's production process (Figure C-9), replacing the leading technology options that had received venture capital funding. No patents were derived from the funded work, which built on demonstrating already-patented inventions, and the company did not publish its results. Neither the seasoned management team nor the ARPA-E program director required T2M involvement as the program director was able to provide both the technical and business advice needed. Both 1366 Technologies and the program director believe this is likely the best scenario, with a single director providing whatever the performer requires so that the project's direction can pivot to address its greatest challenge. In the case of 1366, this was a technical challenge; in other cases, the challenge relates to the product.

Committee assessment 1366 Technologies is well on its way to becoming a successful company. The company received private-sector investment and construction commenced in 2017 on the first commercial solar power plant utilizing its technology. It has not pivoted away from its initial mission and continues commercialization of the PV technology ARPA-E funded. 1366 benefited from ARPA-E investment since it allowed the company the flexibility to investigate manufacturing options. Follow-on funding was also favorably impacted by ARPA-E selection in a highly competitive OPEN solicitation. If in the future, 1366 Technologies is a successful producer of solar cells that will be due in large part to early ARPA-E funding and the freedom it accorded the company to explore. ARPA-E will have demonstrated the ability to nurture an emergent, transformative technology.

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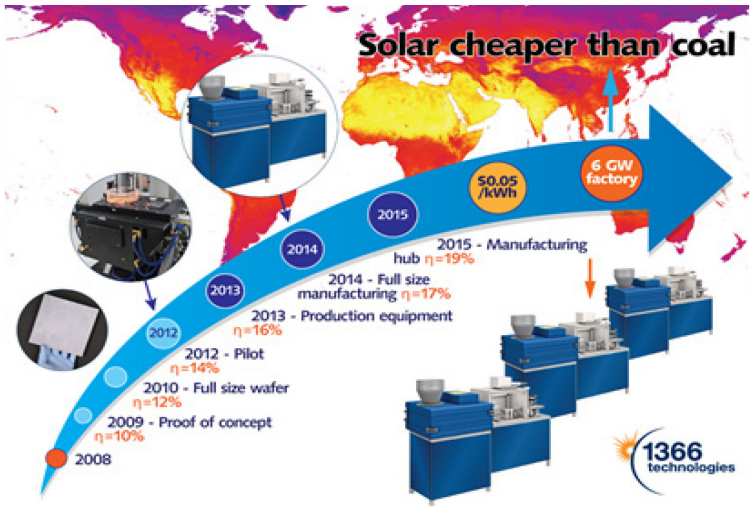

FIGURE C-9 1366 Technologies' growth as a company.
NOTE: The ARPA-E period was from 2010 to 2012.
SOURCE: 1366 Technologies, 2010.

Semi-Solid Flowable Battery Electrodes (24M)

Project description Li-ion batteries offer many advantages for use in vehicle and electricity grid applications because of their higher energy densities, lower weights, and faster charging capabilities compared with other battery chemistries. The 24M team initially proposed crossing a Li-ion battery with a fuel cell to develop a semisolid flow battery, with the conventional Li-ion active materials suspended in a slurry (semisolid mixture). However, the 24M team determined early on that using the slurry to fabricate thick electrodes in a Li-ion battery cell was a more promising approach. The slurry allows the delivery of the active Li material in the form of a film of closely packed particles. The new cells provide higher energy density than state-of-the-art large-format Li-ion cells because they allow a larger ratio of active to inactive material. Further, this design is much simpler to manufacture. The use of a single thick film eliminates the need for alternating thin films of anode and cathode materials as in traditional cells. 24M says its batteries could have a 15–25 percent increase in energy density and be produced in one-fifth the time in much smaller plants compared with traditional Li-ion battery cells. Achieving these metrics could allow batteries to become cost-competitive for grid and vehicle applications (ARPA-E, 2016d; Woyke, 2016).

Project funding characteristics 24M received an ARPA-E award of $5,975,331 as part of the BEEST competition in the technical category of transportation storage (Figure C-10). The project term was from September 1, 2010, to February 28, 2014.

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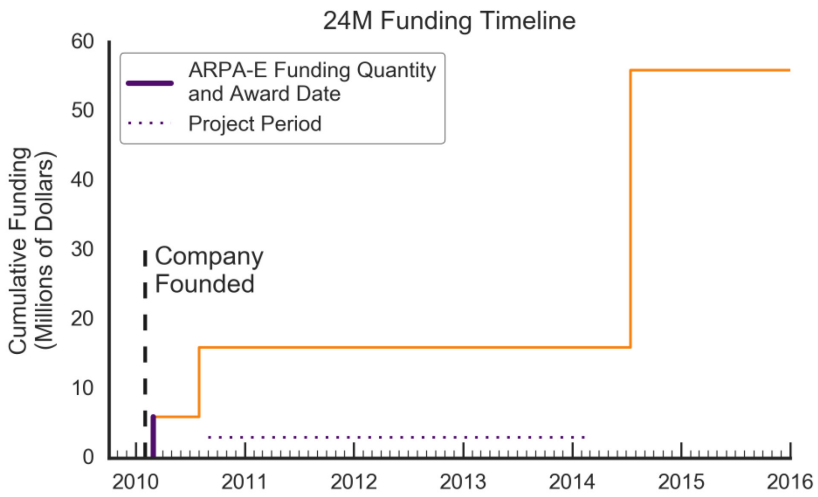

FIGURE C-10 Funding history for 24M.
NOTES: The figure shows the timing for the company's inception, for the ARPA-E funding (purple), and for external funding from other sources outside the ARPA-E funding time period (orange). 24M received $6 million as part of the BEEST (Batteries for Electrical Energy Storage in Transportation) program. The project term was from September 1, 2010, to February 28, 2014. After ARPA-E funding ended, 24M received $10 million in Series A funding and subsequently $40 million in Series B funding. The scales and timeframes in this chart vary and therefore should be compared with caution.
SOURCE: ARPA-E, 2010.

Early project challenges In 2008, Dr. Yet-Ming Chiang of MIT was on a 1-year sabbatical as a full-time employee at A123 Systems, a battery company that he had previously founded. During that sabbatical, he conceived the idea of a semisolid Li-ion flow battery. A123 was unable to fund the development of an entirely new technology at that time but gave Dr. Chiang its blessing to pursue the concept at his MIT research lab. Dr. Chiang subsequently obtained a $50,000 DARPA seed grant to develop the idea. However, at that point, DARPA was reducing its support for energy research, in part because of DOE's increased investments in the area, and Dr. Chiang needed additional sources of funding to continue the research. He faced two main challenges in getting funding from ARPA-E.

The first challenge was developing a proposal that ARPA-E would fund. In 2009, ARPA-E was a new agency, and Dr. Chiang applied to its OPEN funding solicitation of that year, the agency's first funding solicitation. The reviews of the proposal were generally negative, including the comment, "As novel as this idea is, it is not clear if it would have a transformational impact on the industry.…" The proposal evaluation procedure in place did not allow for rebuttals, and the project was not funded. However, Dr. Chiang had previously discussed with the program director, Dr. David Danielson, his past experience in obtaining funding from DARPA—from which ARPA-E had derived its name and some of its mission. Dr. Chiang had pointed out how at DARPA, the program managers did not make decisions based solely on outside peer reviews, and that giving program managers greater discretion was a critical element of DARPA's ability to select radical and risky new ideas. Dr. Chiang applied a second time, this time to the BEEST program at Dr. Danielson's recommendation. ARPA-E had by now changed its approach to allow proposers the opportunity to rebut reviewers' comments. This time the project was funded.

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The second major challenge was getting funded by ARPA-E while being affiliated with both a start-up company and MIT. Despite winning the award from ARPA-E, Dr. Chiang still was hampered by the conflict-of-interest policies in place at the university. Specifically, MIT's Office of Sponsored Programs (OSP) did not allow a professor's MIT laboratory to receive research funds from a sponsor that simultaneously funded a start-up company in which the professor was a shareholder. Although ARPA-E wished to fund the project both in Dr. Chiang's MIT lab and at 24M, no progress toward allowing this arrangement was being made at MIT. One night Dr. Chiang received a call from a DOE official saying that if MIT could not sort out its policy, the agency would give the funding to another project. This call was groundbreaking because the threat of losing this funding created the urgency for MIT's OSP to finally sort out the problem. A conflict-of-interest management plan was created in which the dean of engineering and the head of the Materials Science and Engineering Department had oversight, and this solution finally allowed for the research to be conducted.

Project execution In the early years of ARPA-E, venture capital interest in clean technology was very high. In this environment, ARPA-E funding almost had the role of being a "stamp of approval." Specifically, in a way that is probably not as prevalent today, ARPA-E funding in those early years of the agency's existence could help make follow-on funding more likely. In the case of 24M, just after receiving ARPA-E funding, the company received $5 million each from North Bridge Venture Partners and Charles River Ventures.

A critical element of this project was the open communications Dr. Chiang had with his initial program director, Dr. Danielson. In Dr. Chiang's words, "Everyone knows, when pitching a proposal to DARPA, you need to have very aggressive milestones. As soon as DARPA decides to fund you, you then want to make sure you can meet your milestones, and there's always a significant negotiation with your [program manager] on the details of the milestones."

Within the first 3 months of obtaining ARPA-E funding, 24M realized that its semisolid flow cells concept was actually less commercially promising than recent results focused on flowable and manufacturable binder-free electrode structures.[5] With this knowledge, 24M made a significant pivot and abandoned the entire concept of a flow cell to start working on thick electrode batteries that do not flow at all but can be made cheaply and efficiently relative to traditional battery structures (Figure C-11). The company believed that these batteries would be accepted more readily by the marketplace for long-duration stationary applications. 24M kept this information to itself, continuing for the next 5 years to let many outside the company believe it was developing a flow battery for automobile applications. At the same time, Dr. Chiang shared openly with Dr. Danielson the insight that the technology could be applied in either market. In Dr. Chiang's words, "One really good thing about ARPA-E is that the security around information within ARPA-E is great. Sometimes I wish they would tell me more about other performers, but they don't." As a consequence of the ability to be open with his ARPA-E program director, Dr. Chiang and his colleagues were able to execute such a fundamental pivot and to secure follow-on funding from the GRIDS program, led by Dr. Mark Johnson.

[5]24M ran its own internal techno-economic analysis (something ARPA-E later developed internally) and realized that the cost advantage of a flow battery diminished as the energy density of the flow electrodes increased, such that the high energy density of 24M's flow electrodes favored a nonflow architecture.

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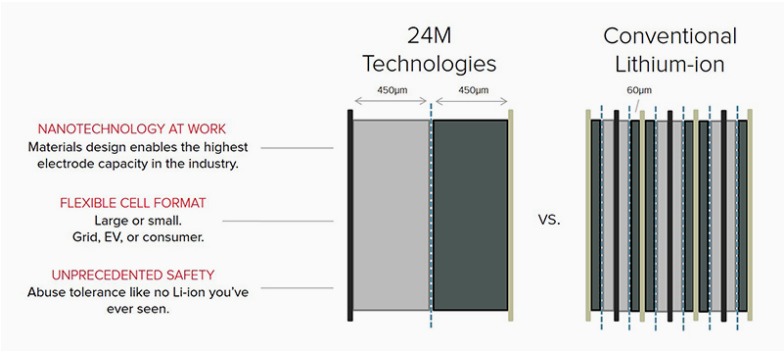

FIGURE C-11 Schematic of 24M Li-ion battery cell versus conventional Li-ion cell.
SOURCE: Image courtesy of 24M Technologies, Inc.

One of the early views Dr. Chiang shared with Dr. Danielson was that he believed it was critical for ARPA-E to retain DARPA's go/no-go milestones. From Dr. Chiang's perspective, the path of 24M had changed so much that the particular milestones themselves were not as important as the pressure and expectation for output created by having milestones (which had been negotiated to accommodate the significant change in technology direction).

Technology-to-market prospects Although 24M raised funding from U.S.-based venture capitalists in its Series A round, it was unable to attract U.S.-based strategic investments for its Series B round. Of three potential U.S.-based strategic investors, each a large company, one was focused on developing a market for new active materials of its own and was not sure that 24M's approach would help it grow that market. A second potential strategic investor with which 24M had discussions was already deeply committed to developing a new battery technology of its own. A third company told 24M that its reason for not investing was that by the time 24M approached the technology, it was too far along for the company to capture core intellectual property. As a consequence, 24M ended up with two strategic investments coming from Japanese companies and one from the former national oil company of Thailand.

Despite being a world expert in battery technology and an experienced serial entrepreneur and having the opportunity to obtain input during the early stages of ARPA-E funding, Dr. Chiang believes in retrospect that 24M would have benefited from earlier connections to U.S.-based strategic investors, since they are the most likely funders of developing energy technology companies. Dr. Chiang suggested that making connections with strategic investors and experienced venture capitalists who are creative thinkers is an important area for growth within ARPA-E. He also emphasized that ARPA-E needs to recognize that the path to commercialization is scale-sensitive. How best to demonstrate a prototype or engage a commercial partner depends on the scale of the product. There is much greater risk in demonstrating large-scale projects—for example, nuclear power plants or even large-scale flow batteries. Requiring that the demonstration work the first time in such large-scale projects can kill important technologies. 24M's ARPA-E project produced three issued patents during its duration; today that portfolio has grown to about two dozen.

ARPA-E's role In this project, ARPA-E was very amenable to changing goals and milestones to accommodate 24M's new findings as it changed technical directions. ARPA-E appears to have succeeded in supporting the new concepts being introduced and in helping the project team maintain momentum while it altered some key aspects of the project. The leadership of 24M is

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extremely seasoned and as such clearly did not need a significant amount of T2M support, although as noted above, connections with more strategic U.S. investors would have helped. The company did, however, benefit from the support and oversight of some particularly strong program directors.

Slippery Liquid-Infused Porous Surfaces (SLIPS): Harvard University

Project description Harvard University developed various slippery surface technologies for making materials and coatings that can achieve extreme energy savings in many industrial settings, including merchant shipping, oil and water pipelines, wastewater treatment systems, solar panels (to prevent dust accumulation), and refrigeration (to prevent ice buildup). The idea for SLIPS was inspired by the slippery surface of the carnivorous pitcher plant, which uses liquids and a mechanical trap to catch insects. By copying the plant's systems, the Harvard team developed a porous material that could hold liquid similarly to the way a sponge holds water. ARPA-E guided the team to investigate commercial applications for the technology and select those with the greatest promise. After a 6-month exploratory effort, the team, together with ARPA-E, chose to develop a SLIPS coating for refrigeration coils that would reduce defrost cycles by enabling faster shedding of frost and water from the surface of the coils. The team tested large-scale SLIPS-coated coils at LG and other local coil-producing companies and demonstrated significant energy savings. After 2 years, sufficient proof-of-concept had been established to prompt the launch of a start-up company, SLIPS Technologies, Inc. (STI) to commercialize SLIPS. STI was launched in October 2014 with financing from the venture capital arm of BASF, a chemical company. Following the spin-off, ARPA-E extended funding for a third year to enable exploration of SLIPS coatings that could prevent marine fouling on ship hulls so as to reduce drag and improve fuel efficiency in various marine applications. Early results demonstrate the potential of SLIPS to address unmet needs in that market with a nontoxic alternative to current antifouling coatings (ARPA-E, 2016f).

Project funding characteristics Harvard received an ARPA-E award of $2,749,998.00 as part of the OPEN 2012 competition (Figure C-12). The project term was from April 26, 2013, to July 25, 2016.

Technology overview A team of scientists led by Harvard University Professor Joanna Aizenberg submitted a proposal to ARPA-E for the development of SLIPS. Dr. Aizenberg and her team are part of the Harvard University Wyss Institute for Biologically Inspired Engineering and the School of Engineering and Applied Sciences (SEAS). The SLIPS technology repels virtually all liquids and biological fouling agents from almost any surface and under many different conditions. It does so by attaching a liquid to the substrate in a novel way to produce a nonsticky slippery surface (see Figure C-13). SLIPS is a friction-free coating with the goal of achieving extreme energy savings in many industrial settings.

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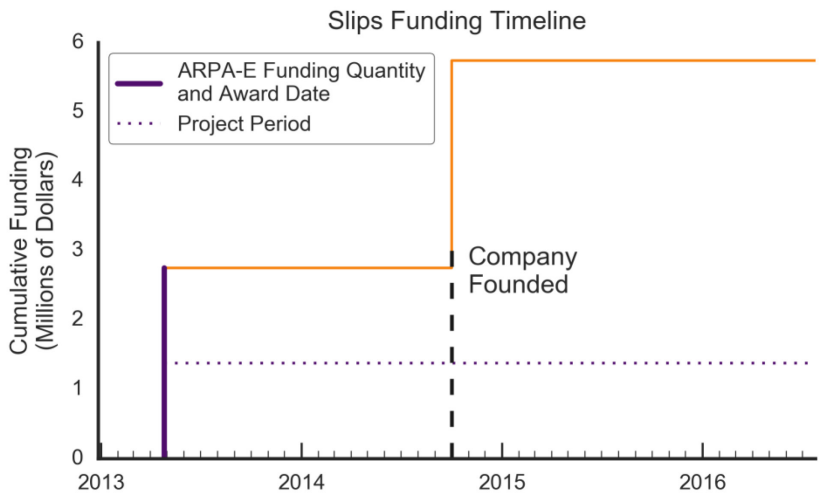

FIGURE C-12 Funding history for SLIPS.
NOTES: Harvard University received an ARPA-E award of $2.750 million as part of the 2012 OPEN Funding Opportunity Announcement. The project term was from April 26, 2013, to July 25, 2016. A year and a half into the project, BASF Venture Capital raised $3 million in the initial financing round in October 2014 to create a start-up company, SLIPS Technologies, Inc.
SOURCES: crunchbase.com, arpa-e.energy.gov, links from slipstechnologies.com/news, including betaboston.com.

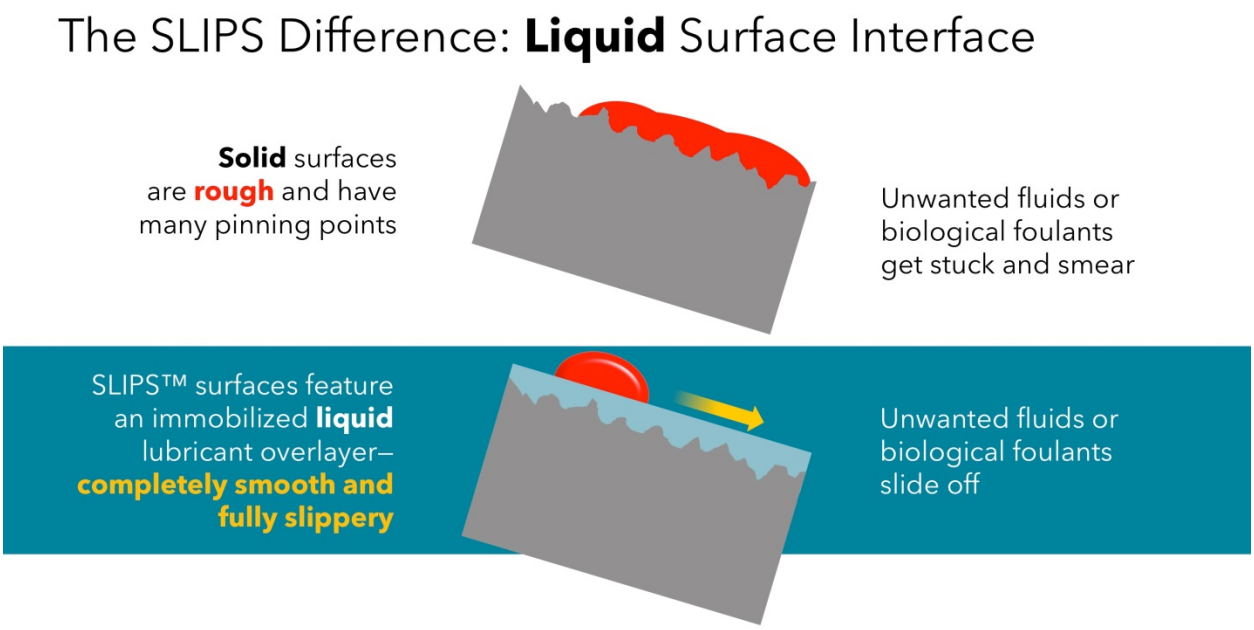

FIGURE C-13 Compared with a solid surface, a SLIPS surface features a stable and immobilized liquid lubricant overlayer that presents a liquid interface.
NOTE: This "liquid surface" is perfectly smooth and has no pinning points onto which fouling agents can become stuck. This is what makes SLIPS ultra-slippery and highly repellent.
SOURCE: SLIPS Technologies, 2015.

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Technology-to-market prospects The proposal to ARPA-E outlined a plan for developing the technology and applying it to fluid handling in oil pipelines and water circulation systems. New systems in these sectors often take 20–25 years to adopt new technologies. During the project's kickoff meeting, Dr. Aizenberg highlighted the numerous industrial uses of the technology—for example, reducing the effects of icing on refrigeration coils, repelling marine fouling, and preventing bacteria from sticking on medical equipment.

Given the many potential applications for SLIPS, ARPA-E asked Dr. Aizenberg to spend the first few months of the project evaluating 10 different energy sectors through small proof-of-concept experiments, market research, and discussions with potential industrial partners. Dr. Aizenberg described the process as a combination of spreadsheet analysis with go/no-go questions to analyze trade-offs of costs, timing, and impact, and assessment of feasibility through small experiments. This process took 6 months and identified two applications viewed as having near-term probabilities of success: (1) refrigeration and reduction of defrosting cycles and frost formation on refrigeration coils, and (2) wastewater membranes and reduction of membrane fouling. Neither of these two applications was in the original proposal to ARPA-E. The project team chose refrigeration as its primary focus, and ARPA-E agreed to fund the project for 2 years, which included the time spent on the market analysis.

Dr. Aizenberg met with representatives from BASF at the ARPA-E Energy Innovation Summit. BASF also had a history of working with and sponsoring research programs at Harvard University and had followed the progress of SLIPS with great interest. In June 2014, Dr. Aizenberg and her collaborator, Dr. Philseok Kim, founded STI. With help from BASF, Drs. Aizenberg and Kim brought in an experienced start-up chief executive officer to run the company, and Dr. Kim left Harvard to join the company full time as chief technology officer. The company is commercializing SLIPS materials and coatings for applications in industrial, consumer, and medical applications, with the development of a marine foul-release coating being a major emphasis. This project is a successful example of ARPA-E helping a principal investigator's team scout out commercially relevant applications for an innovative material, establish proof-of-concept, and then transition the effort to a commercialization path via a start-up company.

Following the spin-off, ARPA-E extended funding for a third year to enable further exploration of marine applications. Dr. Aizenberg said, "Testing and applying SLIPS to the marine environments area is challenging and interesting because nobody has solved it yet." Initial research indicated that SLIPS has the potential to be a useful, environment-friendly substitute for toxic antifouling paints and coatings and to address the need for an effective foul-release coating for slow-moving merchant vessels.

Outcomes and ARPA-E's role As described above, the project led to the creation of a company, STI. The principal investigator, Dr. Aizenberg, is a co-founder, a director, and chair of the Scientific Advisory Board of STI. The project produced five to seven patents, more than 10 publications (including 6 in *Nature* family journals), and several press releases. In addition, according to Dr. Aizenberg, ARPA-E transitioned the "down-selection" spreadsheet analysis developed by her team to help other companies and ARPA-E teams.

From the principal investigator's perspective, ARPA-E's flexibility and ability to adjust project goals and metrics helped the project team achieve meaningful technology goals. Dr. Aizenberg highlighted ARPA-E's deliberate interest in identifying the right technology and market for their innovation, as well as its insistence on a rigorous due diligence process to identify such markets. She was particularly appreciative of the support and guidance she received

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in areas in which her team (at that time) was not proficient—such as market analysis—and noted that ARPA-E was able to connect her to an external market analysis team when necessary. Focusing on early market adoption enabled research to continue on applying the technology in more complex areas. The principal investigator did note, however, that a quarterly reporting process with less paperwork, fewer meetings, and simplified reporting would have allowed more time to be devoted to research.

Committee assessment The idea of using a liquid–liquid interface (with one liquid adhered to a solid surface) as a mechanism for reducing friction is a novel one. ARPA-E's decision to fund this project even without concrete results and then guide the team through an exploratory evaluation is representative of a bold approach to funding. The first application of the technology (refrigerator coils) required out-of-the-box thinking, meeting ARPA-E's mandate specifically to deploy advanced energy technologies to reduce energy usage. Following the spin-off dealing with refrigerator coil development, the team correctly focused its attention on exploring marine antifouling applications. This is the current way to develop technologies based on a materials innovation—identify specific applications that can offer commercial value quickly and then build upon them. However, it is too early to say whether this technology will change how industry deals with friction.

Laser-Mechanical Drilling for Geothermal Energy (Foro Energy)

Project description Foro Energy has developed a unique capability and hardware system for transmitting high-power laser light over long distances via fiber optic cables to ablate or weld materials. Long-distance transmission of high-power lasers was believed to be impossible because of distortions to light that would occur through fiber optic cables. Foro's system engineers the cable, laser source, and system simultaneously to eliminate these distortions. This laser power is integrated with a mechanical drilling bit, and the laser energy softens the rock, allowing the mechanical bit to remove the rock more easily. This system enables rapid and sustained penetration of hard-rock formations that are too costly to drill with mechanical drilling bits alone. Not only did ARPA-E provide critical early funding, but it also provided the company with a stamp of technical credibility. This level of due diligence, along with exposure to the technology through the annual Energy Innovation Summit, helped Foro obtain follow-on funding with venture capital and industry partnerships (ARPA-E, 2016e; Foro Energy, 2016).

Project funding characteristics Foro Energy received an ARPA-E award of $9,141,030 as part of the OPEN 2009 competition. The project term was from January 15, 2010, to September 30, 2013. The company has attracted and received significant follow-on funding.

In the economic downturn that began in September 2008, funding for innovative technologies was difficult to find. Soon after the founders created Foro Energy and obtained seed funding from venture capitalists, they learned about the creation of ARPA-E and the OPEN 2009 program.[6] They submitted a concept paper to ARPA-E in late spring 2009 and by January 2010, had signed a contract for an award. Executing this funding agreement on a relatively rapid basis was critical for Foro. ARPA-E also negotiated a technology investment agreement,[7] which was a

[6]The website for the OPEN program is http://arpa-e.energy.gov/?q=arpa-e-programs/open-2009 (accessed July 28, 2016).

[7]The contract states that "ARPA-E may negotiate a TIA [technology investment agreement] or 'other transactions' agreement in order (1) to encourage for-profit entities to participate in projects in which they would not otherwise

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deviation from a standard cooperative award. The technology investment agreement allowed Foro Energy to pay back the award with interest and thus have complete ownership of its intellectual property, without the possibility that the government could "march in" and provide licenses to other companies for development of the technology.[8] Foro Energy's founder and principal investigator, Joel Moxley, highlighted the use of the technology investment agreement as an example of ARPA-E's willingness to be responsive to the needs of a small company.

Technology overview Foro Energy was officially started up in early June 2009, although the move to launch the company started in 2008. The company was created based on R&D during the previous decade in academic and industry research settings, including Colorado School of Mines. Foro's next steps were to test its hypotheses through experimentation and application. By the time the company learned it would receive an ARPA-E award, it had resolved some of the scientific challenges related to the light-scattering issue.

The key technology developed by Foro Energy was marrying advances in high-power fiber lasers to fiber optic technology to deliver high-power laser light to hard rock down a bore hole. High-power kilowatt fiber lasers that were compact, transportable, and efficient became available. Optical fiber technology was readily available for the communication industry. The challenge for Foro Energy was to eliminate nonlinear optical effects such as stimulated Brillouin scattering, which limited optical power transmission through an optical fiber. The solution to this problem was to modify the spectrum of the high-power laser in such a way that these coherent nonlinear optical effects were suppressed. With this advance, Foro was able to field a system useful for boring holes in hard rock and welding metal pipes.

Foro has created a fiber optic cable that is protected from high temperature, pressure, and vibration with packaging techniques similar to those of low-power fiber counterparts, including corrosion- and crush-resistant armoring and vibration-isolating buffers. Conventional methods drill, work over, and complete energy wells using mechanical cutting/grinding, explosives, harsh chemicals, and high pressures. High-power lasers enable fundamentally new performance capabilities, including

- *precision*, because they can be directed with millimeter accuracy;
- *speed*, because they can cut and destroy materials rapidly; and
- *safety,* because they can be controlled at the speed of light.

The original proposal by Foro was to develop this high-power laser technology for drilling in hard rock to tap geothermal energy. Hard rock is particularly difficult to drill. With Foro's system, the laser light is combined with a mechanical drill to enable a new efficient drilling technology. Although the Foro system appears promising for the geothermal energy application,

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participate; (2) to facilitate the creation of new relationships among participants in a team that will foster better technology; (3) to encourage Prime Recipients to use new business practices that will foster better technology or new technology more quickly or less expensively; or (4) to enhance U.S. economic and energy security and/or maintain U.S. technological leadership in key energy sectors." The website for the award guidance is http://arpa-e.energy.gov/?q=arpa-e-site-page/award-guidance#Patent%20Class%20Waiver%20for%20FY13%20and%20FY14 (accessed July 28, 2016).

[8]35 U.S. Code § 203. March-in rights allow the government to require licenses to be granted, or to grant licenses, in certain circumstances, such as if the organization has not taken effective steps to achieve practical application of the invention.

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numerous uses for the technology are still being developed. The system is currently well suited for cutting and welding metal.

Technology-to-market prospects Foro Energy worked with ARPA-E to create technical and quantitative metrics that initially aligned with what the company proposed in its application. After a surface demonstration with a customer, Foro realized that the metrics needed to be adjusted to put more emphasis on near-term commercialization applications (well decommissioning) and stretch goals for drilling in hard rock. Foro therefore turned its attention to the development of the power cord for the final phases of the project.

Based on feedback from potential customers, Foro undertook the negotiation of new milestones with ARPA-E. According to Foro, "ARPA-E pushed back and wanted to understand the drivers for changes; they [ARPA-E] worked through those changes as a team…and we [Foro] met all of their milestones." The new metrics allowed Foro to focus on core hardware aligned with customer needs, which kept its start-up roadmap on track. The flexibility to modify milestones is an important tool for ensuring that resources are expended on solving problems to optimize the overall success of the effort.

Foro obtained follow-on support from a customer to continue its system development, including building on the original platform to increase the bit size and significantly increase the laser power. These system enhancements are operational as an ongoing program. This program ventures into proprietary material, but it is being pursued aggressively within the company. Intermediate markets have had economically attractive and transformative impacts on health, safety, and the environment, and these enormous societal benefits have been realized even though they were never a specific focus of ARPA-E.

Outcomes and ARPA-E's role Foro Energy has 45 patents, 17 of which list ARPA-E in the government interest section. These patents have more than 2,000 patent claims.[9] According to the company's chief technology officer, Foro's method of using fibers is proprietary, but the goal is to optimize the efficiency of the fibers. The ARPA-E award allowed Foro to develop its intellectual property and, through experimentation, put it into practice. The company's focus during its Series A financing was on the ARPA-E project. The funding allowed the company to focus on nearer-term goals, such as decommissioning and the development of a specialized power cord, which set the stage for achieving its longer-term goal of drilling hard rock. In 2013, Foro received additional funding from DOE's Geothermal Technologies Office "to design a high-power laser system and laser-based well completion tool that could enable unique geothermal downhole well applications with the potential for superior thermal contacting between the wellbore and the surrounding geological formation" (DOE, 2013b).

By the end of ARPA-E funding in mid-2013, Foro Energy had created customer programs and developed offerings in four main application areas: (1) decommissioning, (2) production, (3) pressure control, and (4) drilling. The company is currently in the early stages of commercializing the decommissioning application and expects revenues soon, as it has created commercial units and obtained signed contracts and is conducting field demonstrations on remaining applications.

[9] 35 U.S. Code § 112. The law requires that, to obtain exclusive rights on an invention, the patent applicant point out and distinctly claim in technical terms the subject matter that the inventor regards as his or her invention.

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Joel Moxley noted that this project is a good example of the need for an ecosystem that includes academic research, venture capitalist financing, government funding, and industry interactions to scale up and commercialize the technology. The different perspectives and insights from these voices and partnerships provide the energy and stimulation to accelerate the research.

Over the course of the project, Foro Energy had three program directors who provided targeted guidance and were described as "excellent." The transitions to each new program director were seamless. The ARPA-E contractor, a former weapons inspector, was described as a "technical asset" throughout the project. He also helped with billing and other logistics. The ARPA-E program directors and contractor worked as a team to provide continuity. Moxley stated that "there's a huge value to having a quarterly technical check-in. This is a big forcing function. On the T2M side, we received introductions via ARPA-E and many that led to partnerships."

ARPA-E funding gave the company credibility, and many customers heard about Foro Energy through ARPA-E. The agency's Energy Innovation Summit is the only energy technology conference that Foro attends. The summit has critical mass around the ecosystem and has value for Foro as a company and as individuals given that the peer support network is critical in innovation ecosystems. The company continues to attend the summit annually, in part because ARPA-E has been such a good partner, and Foro wants to support other companies on the same path.

Committee assessment While the process of drilling holes into the earth has changed since its earliest days, it still involves shattering rock and removing the chips for such varied purposes as extracting geothermal energy, crude oil, and natural gas and tunneling. The novel application of well-known laser technology developed by Foro Energy may facilitate a radical new drilling method. This project was envisioned as an enabler for creating cost-effective geothermal energy power plants. The initial goal of the project was to drill hard rock. Foro Energy had the capability to accomplish the laser portion of the project but not to make a drill bit. The company has recognized this and has formed partnerships to implement a laser-augmented drill bit. It appears that Foro is on track to test the feasibility of the proposed approach.

The laser fiber optics of the project have already been developed and demonstrated; the major technical risk that remains is whether a kilowatt of laser light power can be integrated into a drill bit with the Foro technology. Integration with a drill bit is a work in progress. If everything is successful, this new technology could lower the cost of drilling through hard rock, and geothermal energy could become a viable and important energy resource. It is too soon to measure the impact of the ARPA-E project on the technical world, but Foro did deliver high-power laser energy at a distance using an optical fiber. This approach would also be useful for welding or cutting metal in such areas as manufacturing and oil well decommissioning. While there are other ways of achieving improvements in these applications, the fiber optic approach appears most promising. The ARPA-E investment in Foro has accelerated the application of a technology that has the potential to create a sustainable and carbon-free energy resource. At the moment, what has been achieved would tend to be described as more evolutionary than revolutionary. If, however, dramatic success is achieved in drilling hard rock very cost-effectively, this evaluation may have to be revisited.

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Distributed Power Flow Control (Smart Wires)

Project description Modernizing the electrical grid requires the ability to integrate renewable energy sources into the grid and increase controllability to obtain more throughput. Research aimed at achieving these two goals is high-risk. The 300,000 miles of high-voltage transmission lines in the United States today are congested and inefficient, with only around 50 percent of all transmission capacity being utilized at any given time. ARPA-E funding allowed Smart Wires to develop a solution for controlling power flow within the electrical grid to better manage unused and overall transmission capacity. Smart Wires' devices clamp onto existing transmission lines and control the flow of power within the lines, similar to how Internet routers allocate bandwidth throughout the web. This technology could support greater use of renewable energy by providing more consistent control over how that energy is routed within the grid on a real-time basis. This capability would alleviate concerns surrounding the grid's inability to store intermittent energy from renewables effectively for later use. The Smart Wires technology provides a new way of thinking about how grids should be planned and how power flows can be controlled. The principles behind this technology are modularity with rapid deployment and ease of redeployment. Utilities can now invest in a scalable and mobile solution that can be redeployed as needs change. ARPA-E played an important role in guiding the research, introducing funders, and creating an advisory board to assist in testing and demonstration of the technology (ARPA-E, 2016c).

Project funding characteristics Smart Wires received an ARPA-E award of $3,977,745 as part of the GENI competition (Figure C-14). The project term was from April 23, 2012, to September 30, 2014.

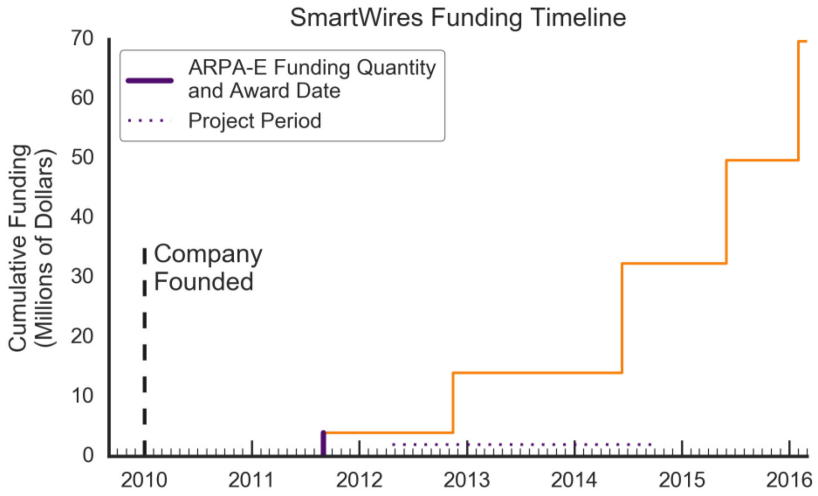

FIGURE C-14 Funding history for Smart Wires.
NOTES: The figure shows the timing of the company's start-up, the ARPA-E funding (purple), and external funding from other sources (orange) and their amounts. Smart Wires received an ARPA-E award of $3.978 million as part of the GENI (Green Electricity Network Integration) program. The project term was from April 23, 2012, to September 30, 2014.
SOURCES: crunchbase.com, ARPA-E.

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Technology overview In the early 2000s, Dr. Deepak Divan, a professor at Georgia Institute of Technology (Georgia Tech), used steel alloys to create a prototype of a distributed series reactor (DSR), a device for controlling power flows over electrical grids by changing the degree of resistance on individual lines. The basic concept was that because electric power flows along the line of least impedance, a device that could modify the degree of impedance on a given line could increase or decrease the flow of power over that line without physically closing the wire. The potential value of the technology was to provide congestion relief on overloaded lines by redistributing power flows, thus improving the performance of the entire system.

A group of utilities interested in the DSR concept incubated the work at Georgia Tech for roughly 9 years, with each utility contributing small increments of funding to enable Divan's team to continue its research, as well as to support preparation of several small-scale studies of the potential benefits of the technology (the so-called "focus initiative"). The utilities supported DSR research through the National Electric Energy Testing Research and Applications Center (NEETRAC) at Georgia Tech, a research center comprised of energy companies and utilities. Divan's research assistant, Frank Kreikebaum, moved to NEETRAC to serve as project manager. In 2009, Kreikebaum formed a consortium within NEETRAC—the Smart Wire Focused Initiative (SWFI)—with a group of utilities (including the Tennessee Valley Authority, Southern Co., Baltimore Gas and Electric Company, and the National Rural Electric Cooperative). NEETRAC worked with SWFI to develop specifications for DSR, including high-current fault testing (63,000 A or 63 kA), impulse testing (±750,000 V or 750 kV), and Aeolian vibration testing. Participating utilities established rigorous performance targets for DSRs, which included speed of installation, high levels of fault withstand, and low power losses. SWFI utilities and Smart Wire Grid jointly designed an installation tool for use on bucket trucks, enabling quick installation of DSRs.

Technology-to-market prospects While DSR technology initially appeared promising, no utility was likely to adopt an untested technology for deployment on an existing grid. Utilities have long regarded their primary mission as resiliency (i.e., keeping the lights on). Planning cycles have been long—10–20 years—and institutional resistance to the risks associated with innovation has been high. Given this reality, even if a new technology appeared to be very compelling, investors were resistant to business plans based on a protracted effort to sell a new technology to utilities. It was apparent that the new technology needed to be tested and proven in an operating environment, generating sufficient data and experience to satisfy utilities that the technology was both effective and very safe. But no funding source could be found for such an experiment.

ARPA-E's GENI focused program was created to address challenges to the U.S. transmission system, which included aging infrastructure, short-term changes in demand, and the growing deployment of nondispatchable generation characterized by intermittency (e.g., wind- and solar-generated power). At present, reflecting congestion and inefficiency, only about 50 percent of U.S. transmission capacity is utilized at any given time. ARPA-E sought to fund research themes addressing power flow control in the distribution and transmission of electricity. Goals included enabling 40 percent variable-generation penetration, a greater than 10-times reduction in power flow control hardware, and a greater than 4-times reduction in high-voltage direct current terminal/line cost relative to the state of the art. GENI was budgeted at $39 million with a target kickoff year of 2011.

In 2010, SWFI spun out Smart Wire Grid, Inc. (later renamed Smart Wires), a start-up based in Oakland, California, to participate in ARPA-E's GENI solicitation and to develop prototypes

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built to utility standards. The founder and CEO was entrepreneur Woody Gibson, co-founder of more than a dozen technology-based start-ups in the energy and environmental areas. Smart Wire Grid licensed DSR technology from Georgia Tech Research Corp. in 2011. Smart Wire Grid was backed by a private equity fund run by Arnerich Massena, an investment and wealth-management firm based in Portland, Oregon. Smart Wire Grid developed three product prototypes:

- The PowerLine Guardian uses DSRs to increase impedance and diminish power flows on overloaded wires.
- The Router redirects power flows to less heavily utilized lines.
- The PowerLine Commander monitors control and data aggregation software that enables utility personnel to monitor the system remotely and reroute power if necessary.

In 2012, Smart Wires won a $4 million ARPA-E award pursuant to the GENI FOA to undertake pilot demonstrations of DSR systems on the Tennessee Valley Authority's (TVA) transmission system. In October 2012, 99 Smart Wire DSRs were attached to approximately 20 miles of 161 kV TVA transmission lines near Knoxville, Tennessee. The DSR units, resembling rectangular boxes, weighed about 150 pounds each and were capable of operating either autonomously or with operator control. ARPA-E monitored the performance of the 99 boxes for a year, establishing the fact that the technology relieved congestion on overloaded lines and redistributed power, thereby optimizing operations of the transmission system.

Outcomes and ARPA-E's role Smart Wires is currently facing a different challenge than it did in its early stages—scaling up to meet demand from utilities for its technologies. It created a new product, the Tower Router, for application in 2016, which directly increases the throughput on underutilized lines. The Tower Router is important as it offers utilities a method that transforms the way power is handled on the grid. In 2015, Smart Wires' CEO indicated that the company was collaborating with 25 of the largest global transmission organizations to "see how we can help them achieve their top strategic priorities." In 2015, Smart Wires raised $30.8 million to bring its first product to commercial production. Smart Wires has brought in a former utility CEO, Thomas Voss, as company chairman, and David Ratcliffe, also a former utility CEO, as a member of the company's advisory board. Michael Walsh, an executive at EirGrid, an Irish transmission company, joined Smart Wires in 2015 to support the company's future operations.

The TVA pilot project generated 2 years of data establishing the trustworthiness of the DSR technology and highlighting necessary corrective measures. The TVA reported in 2014 that the installed DSR systems had run continuously for 21 months and remained available 100 percent of the time to provide power flow control and sensing to support TVA's system reliability. The project demonstrated the ability of the DSR technology to reduce power flow by more than 2.5 percent.

A key lesson learned was that acoustic vibration from PowerLine Guardian devices can significantly affect noise levels in the transmission line right-of-way, a problem that was addressed by improving the bolt design and increasing the torque on the bolts securing the units to the transmission lines. In addition, the communication system on three units proved unreliable, a problem resolved by enabling every unit to act as a Cellular Enabled PowerLine Guardian with backhaul communication capability.

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In a second demonstration project (not funded by ARPA-E), Southern Co. initially installed 33 PowerLine Guardian devices along two 115 kW transmission lines managed by Georgia Power Co. Southern Co. subsequently doubled the number of devices used in the demonstration. In 2015, Pacific Gas and Electric Company was reportedly conducting pilot testing of Smart Wires technologies on its system.

ARPA-E's role in the Smart Wires project was to enable the start-up to build, deploy, and test prototype devices in a real operating environment. Quarterly oversight meetings were held with the project manager, Timothy Heidel, and an ARPA-E systems engineering and technical assistance (SETA) consultant, Colin Shouder. The project represented an instance of very late-stage development, with the technology already in existence and ready for field testing. According to Smart Wires, without ARPA-E's contributions, the company might not have continued to exist or, in the best case, would have been 18–24 months behind where it is today. ARPA-E's funding, and the field testing it enabled, served to "derisk" the technology for follow-on investors and made it easier for the company to raise capital going forward. Operationally, the SETA consultant presented the Smart Wires team with what-if scenarios as to how the product might fail when deployed—an exercise that the team has incorporated into its own internal design procedures.

ARPA-E created a set of advisers as well as program and funding structures for the project. It helped Smart Wires understand how to conduct demonstrations, recognizing that if field testing failed, the technology might not receive another trial. The SETA consultant, who was very familiar with grid technologies, worked closely with the company on developing the hardware. Smart Wires personnel considered the program director to be remarkably skillful at covering many bases, but when he did not understand details, he knew enough to defer to the SETA consultant. The T2M adviser, Josh Gould, helped connect Smart Wires with stakeholders, including financial backers, and develop and refine its business skills. As the skills of the Smart Wires team improved, the need for ARPA-E T2M assistance declined.

The Smart Wires project had experienced a major problem when a large partner designing software for the DSR system left the project. The software was necessary to operate the system and assess its benefits in the context of a large-scale system. ARPA-E met with the Smart Wires team and rewrote all of the project milestones involving the software. This course correction in the face of a major unforeseen change was a success and an example of flexible project oversight.

Smart Wires' management attributes the company's success to ARPA-E's engagement. ARPA-E brought funding and rigor to its operations. Money alone was not enough; ARPA-E brought the company access to investors, providing a sort of seal of approval for follow-on funders. The agency's participation generated data and operational test results. Each increment of subsequent investment became easier because ARPA-E made the venture less risky for investors. It is unlikely that Smart Wires would exist today without having had ARPA-E's support in 2012–2014.

Committee assessment There are two major needs in the electricity grid—storage to integrate renewables and controllability to get more throughput from the existing grid. When Congress first provided funding for ARPA-E, the agency's charge was to develop transformative energy technologies that would not likely be privately funded and developed because of their high risk.

Smart Wires' technology has the potential to transform how power grids are planned and operated around the globe. The company has built upon the value developed and tested during the ARPA-E project. The value of Smart Wires is tied to one of the most critical challenges

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facing the grid—controllability for the known, the unknown, and the unknowable uncertainties. Smart Wires technology is not just a clever set of power electronics; it represents a new way of thinking about how grids should be planned and how power flows can be controlled. The principles behind Smart Wires are modularity with rapid deployment and ease of redeployment. Given the many challenges to predicting grid needs, investment in a scalable and mobile solution that can be redeployed as needs change is compelling. There are four key areas in which this technology has the potential to be transformative:

- *Urgent grid needs*—When there is no time to build new infrastructure, Smart Wires technology can be deployed to increase throughput very quickly to solve power flow problems, such as those that result from plant retirements due to the Mercury and Air Toxics Standards (MATS) rule and the clean power plan.
- *Temporary grid needs*—Many infrastructure needs are temporary. Permitting, construction of a new line or generator, or loss of a generator can change flows, and some upgrades that are needed in the short term are not necessary in the long term. Smart Wires gives grid planners the ability to fix the problem and redeploy the power electronics when the need no longer exists.
- *Difficult-to-build locations*—When environmental, land use, or other factors limit the ability to build or upgrade lines, Smart Wires offers a compelling solution entailing considerably less land use and environmental impact.
- *Congestion and renewable energy*—There is some early but compelling evidence that technologies such as that of Smart Wires could be quite effective in moving larger amounts of power from one region to another. Distributing the Smart Wires devices across multiple lines, thus making more use of the existing grid, could be a game changer for reducing congestion, lowering renewable integration costs, and facilitating the development of distant renewable resources with higher capacity factors.

Smart Wires technology has the potential to increase transmission line utilization from the current average of 45–60 percent to 75–90 percent. The cost of a Smart Wires installation is equal to 1–10 percent of the cost of building a new transmission line, excluding costs associated with right-of-way and permitting. Program director Heidel characterizes the Smart Wires project as “transformational” because the new technology enables utilities to modulate the impedance of lines reliably on command. Previously, impedance could be modulated only with fully rated power converters, which were expensive and characterized by low reliability. The breakthrough achieved by the project was the development of data and experience sufficient to convince conservative utility managers to adopt the new technology. Heidel also believes that utility executives’ realization that they can modulate power flows on command will have transformational effects on their decision making and will result in more efficient, lower-cost transmission.

Cancelled Project: Nanostructured Scalable Thick-Film Magnetics (General Electric)

As noted earlier, ARPA-E cancels projects before their original end date if they are not meeting their goals and appear unlikely to do so eventually. As of September 2015, ARPA-E had cancelled 25 of its 440 funded projects, 7 of which were university-led and 18 private company-

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led. Ten projects led by small companies (<500 employees) and 8 by larger companies (>1000 employees) were cancelled.

One case study of a project that ARPA-E cancelled is described here. General Electric (GE) is classified as a large company with a project funded through a focused program. GE conducted research aimed at developing smaller magnetic components for power converters that maintain high performance levels. The magnetic components had the potential to be used in a variety of applications, including solar inverters, electric vehicles, and lighting. In this case, the technical background of the project manager may not have aligned with the needs of the ARPA-E project. The case study describes a feasibility study led by GE that was cancelled 3 months early.

Project Description

Magnetic components are typically the largest components in a power converter. To date, however, researchers have not found an effective way to reduce their size without negatively impacting their performance. GE worked to build smaller components with magnetic thick films, created using the condensation of vaporized forms of magnetic and insulating materials. The project's failure to achieve its milestones was not due to physical limitations but to a cost nearly twice as high as had been anticipated to overcome the technical challenges involved. Although this ARPA-E project was cancelled, it advanced the learning process for bringing the technology closer to commercial feasibility.

Project Funding Characteristics

GE received an ARPA-E award of $811,520 as part of the Agile Delivery of Electrical Power Technology (ADEPT) competition. The project term was from January 1, 2011, to July 17, 2012. The project was cancelled after 15 months, 3 months earlier than scheduled.

Technology Overview

Devices such as inverters and computer power supplies are part of a broad class of power electronics that use rapid switching and magnetics to convert electric power from one form to another. Examples of these technologies include direct current that can be made into alternating current and vice versa.

The ubiquity of these devices means that improvements in available materials will have large impacts. The cost and performance for power electronics are often limited by the magnetics, which are materials such as iron or ferrite (an iron oxide ceramic) that couple magnetic fields from one part of a device to another. The saturation fields limit the size of the magnetics. A common and useful way to make magnetics is to produce ferrite slurries or "green bodies," followed by sintering to produce the desired magnet shape. Ferrite's conformal character, low cost, and adequate magnetic performance make it the default material choice for a wide array of power electronics devices.

GE's plan for this ARPA-E project was to extend the feasibility testing of a replacement for ferrite in power electronics. GE's goal was to develop a replacement power converter with a smaller size that would maintain effectiveness. This effort involved physically depositing a metal composite magnetic material. GE conducted research to prove the feasibility of the technology (technology readiness level [TRL] 4/5) so it could be moved to the next stage of development (TRL 6) and be tested as a component in a systems application. At this TRL level, GE might pick

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up the deposition technology, given its familiarity with the technology, or it might license the technology to a supplier.

GE Research does not usually fund research on components unless they fit within an existing product line. For example, GE does not make magnetics but does source them. Internal GE funding is not generally provided to develop novel processes for suppliers unless the commercial product line is incapable of meeting specifications without changes in supplier capability.

GE did provide limited internal funding for this research in 2004 and received a follow-up DARPA grant during 2004–2005. The research identified a novel iron-based material that had up to four times the magnetic field capability and could also be conformal. GE applied to ARPA-E's ADEPT program in 2010 for funding to support translating the science to practice by demonstrating that improving the field capability, losses, manufacturing rate, and quality would advance the efficiency of commercial devices. The award had clear milestones and targets. The timeline for the project was very short, as is consistent with a feasibility exercise. The team was unable to accomplish the project goals, and ARPA-E and GE mutually agreed to stop work before expending all of the funding.

ARPA-E's Role

The ARPA-E team was very involved technically in the project. The team's technical expertise was in electrical engineering, with a focus on semiconductor devices, which was somewhat complementary to the GE's team's expertise in materials science. Although GE communicated its equipment challenges to its ARPA-E team, a solution that fit with the project's time and resource constraints could not be found. In hindsight, the project might have benefited from extra time to solve its technical challenges, which an ARPA-E team with materials science expertise might have supported. The GE team did not work with the T2M team because of the nature of the project.

Committee Assessment

Although this project was cancelled, the GE Nanostructured Scalable Thick-Film Magnetics project can be viewed as a success in several ways. The project advanced the learning process and state of the art such that the technology more closely approached commercial feasibility. The project ended without arbitrary expenditure of time and effort. The failure to achieve milestones was not due to a physical limitation but to the higher cost (at least twice as high) than had been anticipated. Part of the failure was that the award assumed a well-functioning electron beam physical vapor deposition reactor at GE. Significant unanticipated effort was needed to make the reactor work, by which time the project could not catch up. If the costs can be reduced, renewed efforts to continue to advance this technology are warranted.

Other Projects

The committee categorized projects as "other" if they have resulted in little or no direct energy market success but still have advanced the state of knowledge. Four such case studies are presented here:

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- Agrivida genetically engineered plants to contain high concentrations of enzymes that break down cell walls. These enzymes could be "switched on" after harvest so they would not damage the plant while it is growing. If successful, Agrivida's approach would decrease the production cost of domestic biofuels by up to 20 percent.
- Ceres, Inc. generated new crops using plant biotechnology. Ceres had cloned and sequenced many genes and clustered them into 12,000 functionalities prior to ARPA-E involvement. Traits that affected nitrogen/fertilizer use were discovered. Nitrogen uptake is a challenging trait; little was known about it at the time of ARPA-E funding, and operation at commercial scale with nitrogen genes was (and still would be) a large undertaking.
- HRL Laboratories is conducting research on fabricating transistors vertically to achieve a higher power level. This research is very difficult to accomplish, requiring breakthroughs in processing to achieve manufacturing and economic efficiencies. This is a challenging project that entails many technology ecosystem dependencies and requires manufacturing capabilities.
- Stanford University's radiative cooling device relied on recently developed state-of-the-art concepts and techniques to tailor the absorption and emission of light and heat in nanostructured materials. This research had the potential to enable buildings, cars, and electronics to cool without using electric power, a concept that was widely thought to be impossible. The project did not achieve the expected preliminary cost reductions, and its applications appear distant, but it had the effect of changing all engineering understanding of the limits of practical systems in thermal management.

Engineering Enzymes in Energy Crops (Agrivida)

Project description Petroleum-based fuels are the primary source of power for cars, trucks, and planes. Biofuels produced domestically from biomass might be an alternative. However, the methods used to turn biomass into fuel are currently too expensive and inefficient to make these biofuels a commercial alternative to fossil fuels. Expensive enzymes are required to break plant biomass down into the fermentable sugars that are used to create biofuel. Engineering crops to contain these enzymes would reduce costs and produce biomass that could more easily be digested. Agrivida conducted research aimed at genetically engineering plants to contain high concentrations of enzymes that break down cell walls. These enzymes could be "switched on" after harvest so they would not damage the plant while it was growing. If successful, Agrivida's technology had the potential to significantly decrease the production cost of domestic biofuels, thus helping the United States reduce foreign oil imports. ARPA-E provided plus-up funding for development of the data needed to bring the technology to the market. When a market did not develop, Agrivida changed direction to focus on animal nutrition.

Project funding characteristics Agrivida was funded as part of the OPEN 2009 solicitation at a level of $6,562,723 over the period January 2010 to March 2015. (See Figure C-15.)

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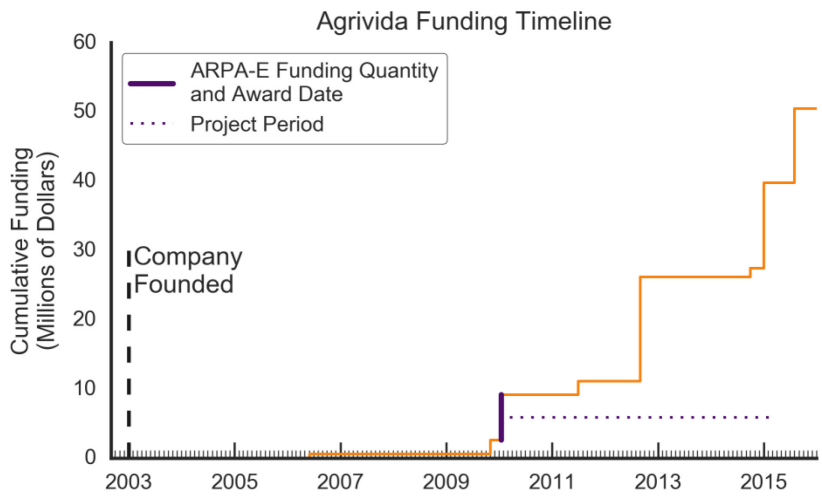

FIGURE C-15 Funding history for Agrivida.
NOTES: The figure shows the timing of the company's start-up, the ARPA-E funding (purple), and external funding from other sources (orange) and their amounts. The company has continued to grow and attract investors. A total of more than $50 million was raised, with $40 million coming after the announcement of ARPA-E funding.
SOURCES: https://www.crunchbase.com/organization/agrivida#/entity; and ARPA-E: http://arpa-e.energy.gov/?q=slick-sheet-project/engineering-enzymes-energy-crops.

Technology-to-market prospects Prior to the ARPA-E grant, Agrivida was an agricultural biotech firm developing crops to produce chemicals, fuels, and bioproducts by engineering the crops to express enzymes. Its research was focused on enabling production of low-cost sugars through the expression of enzymes in the crop. If this approach were successful, Agrivida estimated it could decrease the production cost of domestic biofuels by up to 20 percent. This cost reduction in turn could drive an increase in the production of domestic biofuels and thereby help the United States reduce foreign oil imports by 33 percent in 15 years. The widespread use of biofuels, biopower, and other bio-based products has the potential to conserve 1.26 billion barrels of oil, 58 million tons of coal, and 682 million tons of carbon dioxide from 2020 to 2030. The widespread use of biofuels also would help reduce and stabilize gas prices for consumers.

Outcomes and ARPA-E's role The project was funded through an open solicitation, and targets were set based largely on work proposed by Agrivida. Agrivida established its technology primarily in corn to make it more easily digestible. The target was to make energy crops of interest to DOE—switchgrass and sorghum—more digestible and converted more efficiently into biofuel.

Agrivida generated promising results, and as the award was winding down, the ARPA-E program director inquired about the next step. It was determined that field trials were needed to attract future customers and development. ARPA-E plus-up funding was granted to provide the extra money and time needed to grow the materials in a pre-pilot-scale processing facility at the University of Illinois. The plus-up funding provided the data that the prospective partners wanted, potentially transitioning the technology to the market. In this case, no significant market developed as a result of the additional funding.

While it is unclear whether the larger goals of ARPA-E were met in this particular case, it is clear that the project was moved further along as a result of ARPA-E's flexibility and the ability

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of the program director to adapt to changes that resulted from the research. Subsequent funding was raised, yet the company does not believe that the ARPA-E funding played a significant role in its attaining that funding. The company did not find the T2M efforts fruitful, and believes this was due to the lack of synergies with other programs within ARPA-E and the soft market for new biofuel technology.

Committee assessment This project is good example of plus-up funding being used in an attempt to provide a ramp to the next step for a project. In this case, the extra funding enabled more laboratory success and thus proceeding to field test. This project is also a good example of the flexibility of the program director in moving the project forward and adapting to changing conditions. However, given that the company pivoted away from the energy-related technologies that prompted ARPA-E funding, it appears that the long-term objectives of ARPA-E were not met in this particular case.

Improving Biomass Yields (Ceres, Inc.)

Project description Ceres' research focused on developing bigger and better grasses to improve the productivity of biomass-to-biofuel translation per acre. Ceres developed grasses that grow bigger with less fertilizer relative to available grass varieties. Its research led to the production of hardier, higher-yielding grass that requires less land to grow and can be planted in areas where other crops cannot grow. Ceres conducted multiyear trials in Arizona, Texas, Tennessee, and Georgia that resulted in grass yields with as much as 50 percent more biomass than yields from current grass varieties. The company transformed from a start-up to a publicly traded company, completing a successful initial public offering (IPO) while being funded by ARPA-E. The company subsequently moved away from the energy-related technologies that prompted ARPA-E funding and is no longer focused on energy crops. Land O'Lakes recently purchased Ceres. While the company has been successful, ARPA-E appears to have funded a company that was already aligned with an existing DOE Office of Energy Efficiency and Renewable Energy (EERE) biomass program.

Project funding characteristics The work was funded under the OPEN 2009 solicitation, ultimately receiving $5,089,144 between January 2010 and December 2013. Ceres has had a long funding history, as shown in Figure C-16.

Technology overview Ceres has been consistent in its stated goals and has not wavered in its efforts to generate new crops using plant biotechnology. The technologies are used to vary a variety of plant traits. The focus of this project was on energy crops with higher yield and advantaged cultivation properties. Ceres had cloned and sequenced many genes and clustered them into 12,000 functionalities prior to ARPA-E involvement. Notable for energy, traits that affected nitrogen/fertilizer use were discovered. Ceres had good results for genes that enhanced the efficiency of nitrogen use and sought ARPA-E funding to bring different groups of these genes forward as commercial embodiments. Nitrogen uptake is a challenging trait; little was known at the time, and operation at commercial scale with nitrogen genes was (and still would be) a large undertaking. Ceres' considerable trove of genetic traits, and specifically traits on nitrogen uptake, was highlighted in its ARPA-E proposal. This project did not fit into an established program within ARPA-E.

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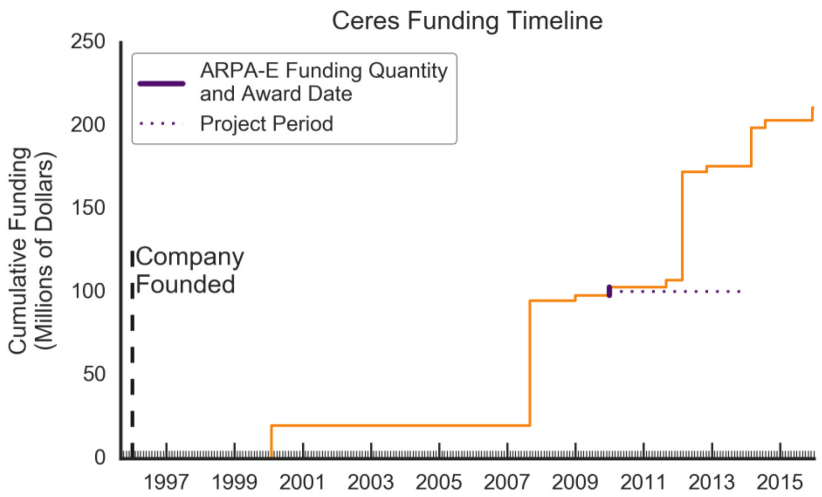

FIGURE C-16 Funding history for Ceres.
NOTES: The figure shows the timing of the company's start-up, the ARPA-E funding (purple), and external funding from other sources (orange) and their amounts. The scales and timeframes in this chart vary and therefore should be compared with caution. Ceres raised a total of more than $200 million, and at the time of ARPA-E funding, had already received other government funding in the biofuels area. Ceres received research funding revenues from several agreements with DOE, the U.S. Department of Agriculture, the U.S. Agency for International Development, and several leading biofuel producers and the Brazilian PAISS Agricola program (Ceres Inc., 2015).
SOURCES: https://www.crunchbase.com/organization/ceres#/entity and ARPA-E: http://energy.gov/articles/ceres-making-biofuels-bigger-and-better.

Technology-to-market prospects If Ceres had been successful and if markets for cellulosic feedstocks had developed, the technology would have significantly decreased the production cost of advanced biofuels. Ceres' work could also be applied to food crops—producing more food crops with fewer resources would lower the cost of food and increase the ability to feed the growing world population. The widespread use of advanced biofuels could displace up to 1.26 billion barrels of oil over 10 years, help prevent up to 682 million metric tons of carbon dioxide from going into the atmosphere over that same period, and decrease nitrogen fertilizer use by 10 percent. Advanced biofuels could follow a path similar to that of first-generation renewable fuels, which contributed more than $53 billion to the nation's 2009 gross domestic product.

Outcomes and ARPA-E's role Ceres' research produced good results for genes that enhanced nitrogen use efficiency, so it sought ARPA-E funding to bring different groups of these genes forward as commercial embodiments. ARPA-E funded development efforts to field trial the stacked nitrogen traits developed by Ceres, which come with considerable uncertainty. Ceres believes the T2M efforts in support of the project were not particularly effective, although the company had good interactions with the T2M team and considered the T2M component one of the positive differences between its ARPA-E funding and other grants. Being highlighted at the ARPA-E Energy Innovation Summit had positive results for Ceres, and the company extensively used the video about its project that ARPA-E produced (DOE, 2013a).

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Toward the end of the project, Ceres became more interested in sorghum than in the other two crops on which it was conducting research. In the final quarter, it made the case for restating and revising its goals and refocusing the final part of the program on biomass and sugar, as it saw the energy crop industry developing in that direction. The program director recognized that the market for biofuels had changed significantly and thus realized that Ceres was right, and worked aggressively to change the goals the project was expected to accomplish. Ceres completed field trials for three crops, with a minor refocus on sorghum, currently a Ceres product, toward the end of the project. As a development effort in which the foundational intellectual property was already in place, the ARPA-E project produced no patents or publications.

Ceres notes that a portion of the R&D used to develop its nitrogen use efficiency trait was funded by an ARPA-E grant. Ceres views the positive press that resulted from being highlighted at the Energy Innovation Summit favorably. The company credits ARPA-E for helping it attract funding and for its completing a successful 2012 IPO.

Committee assessment Ceres transformed from a company that focused on nonfood grasses for advanced biofuels and biopower to one focused on agricultural products. It moved from being a start-up to a publicly traded company, completing a successful IPO while being funded by ARPA-E. The company was bought by Land O'Lakes in June 2017 to work with its subsidiary Forage Genetics International (FGI) (Schaust, 2016).

Ceres raised more than $200 million and, at the time of the ARPA-E funding, had already received other government funding in the biofuels area. In retrospect, it appears that Ceres was on a path that was little altered by the money received from ARPA-E. ARPA-E funding validated the company for investors and, apparently, enhanced the valuation of the company. ARPA-E needs to avoid funding in areas so closely aligned with the main charter of other DOE programs. In this case, during the time of ARPA-E funding for the Ceres project, the Biomass Program within EERE was funding very similar efforts. The traits being researched were known at the time of the funding. Field testing and commercially proving out technology is a difficult but necessary part of moving technology forward. It is, however, difficult to see as a transformative step in this case. This type of project does not reflect the transformative mission to which ARPA-E aspires.

Low-Cost Gallium Nitride Vertical Transistor (HRL Laboratories)

Project description HRL Laboratories, LLC (HRL), an industrial laboratory, is developing a high-performance, low-cost, vertical GaN transistor that has the potential to displace the silicon transistor technologies used in most high-power switching applications today. GaN transistors are expensive to manufacture but have many positive characteristics—they can operate at higher temperatures, voltages, and currents than their silicon counterparts. (See the discussion of the SWITCHES program earlier in this appendix.) HRL plans to combine innovations in semiconductor material growth, device fabrication, and circuit design to create its high-performance GaN vertical transistor at a competitive manufacturing cost. HRL removed weak company partners from its project but now needs to find a partner with manufacturing expertise. The original ARPA-E program director requested market analysis and helped shape the research (ARPA-E, 2013b).

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Project funding characteristics HRL received an ARPA-E award of $2,860,989 as part of the SWITCHES competition. The project term was from March 7, 2014, to March 6, 2017.

Technology overview HRL began discussions on this project with the then SWITCHES program director, Rajeev Ram, and about a year's worth of internally funded R&D data was required before ARPA-E agreed to fund the project. Most transistors in semiconductor chips are laid out flat. This project aimed to fabricate the transistors vertically (i.e., the source, drain, and channel of the transistor are not in the same horizontal plane and therefore are fabricated side by side) but on top of one another. The expectation is that a vertical transistor will offer a higher power level. Most semiconductor processing is done in the planar geometry (with the exception of a certain kind of transistor in dynamic random-access memory structures), and therefore processes, tools, and techniques have been developed for this approach. A vertical approach is more complicated and may have problems with yield and fabrication costs.

Technology-to-market prospects The application of this approach would be for electrical motors and power conversion circuits. Because GaN is a refractory compound with a high band gap, it is particularly suited for high-current, high-power devices, where it competes with silicon carbide, a material that to date has had more practical applications in this arena.

Outcomes and ARPA-E's role ARPA-E benchmarked the project on a regular basis, pushing for cost analysis, competitive analysis, and a T2M strategy. The agency was responsive and flexible, accommodating a delay in schedule and helping to prioritize when the delivery of a large metalorganic chemical vapor deposition reactor for synthesizing the material was delayed. The program director helped shape what was most meaningful to do. The annual ARPA-E Energy Innovation Summit helped HRL form networks.

It appears that the project's selection was due in part to the interest of the program director at the time in GaN technology. There remains some uncertainty about the project's future with a change in program management, and the principal investigator expressed concern about the potential loss of interest on the part of the incumbent program director, as well as the lack of a clear roadmap from ARPA-E in this regard.

The specific application area in this case appears to have been identified by HRL, and ARPA-E's role has been mainly along the lines of program management and evaluation. The agency has done this well, but the selection of the project and project team could have been improved. Vertical transistors are not a new concept, but there are good reasons why they have not been prevalent in the market, related to difficulties in fabricating them economically. Radical innovations are required to make their use practical, and the presence of such radical thinking was not obvious among the project team. HRL partnered with three entities, Virginia Tech, Kyma, and MalibuQ. The two company partnerships collapsed quickly. The process leading to the project's initial selection during the proposal stage was not optimally rigorous.

The principal investigator expressed satisfaction with the thoroughness of the on-site reviews but, echoing other interviewees, expressed some disappointment with the amount of quarterly paperwork that the project team was required to submit.

Committee assessment As noted, the idea of using vertical transistors in semiconductor technology is not new but has not been taken up in the market because it is very difficult to accomplish and would require breakthroughs in processing to be capable of being manufactured and economical. This highly challenging project entailed many technology ecosystem

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dependencies. If a project with such a mandate is selected for funding, it is important to have a committed partner with experience in manufacturing GaN-based semiconductor products and supporting partners with strong experience if one is to have any chance of success. This did not appear to be the case for this project. Two of the partners, MalibuQ and Kyma, appeared to have little experience in the field. To ARPA-E's credit, the partners with weak credentials were quickly removed from the project, attesting to the positive involvement of ARPA-E during the project execution stage. Nonetheless, this project appears to have little chance of success absent firm commitment, from the outset, from a partner with strong manufacturing expertise. HRL, which enjoys an excellent reputation as an industrial R&D laboratory, is not a manufacturer of GaN power semiconductor devices.

Radiative Coolers for Rooftops and Cars (Stanford University)

Project description Stanford University developed and demonstrated a prototype panel of novel cooling material that radiates heat away from structures and sends it directly into space (see Figure C-17). The project team is now scaling its technology to cool water for use in conventional air conditioners and for direct use in the chilled water loops of office buildings, shopping centers, and warehouses. The team is also exploring other commercial applications for its technology, including stand-alone systems or use as a complementary component to larger cooling systems. Reducing building cooling loads reduces pressure on the electrical grid, improving its stability. Better building efficiency and cooling devices would limit electricity consumption and reduce carbon dioxide emissions. Improvements in heating and cooling efficiency also could save homeowners and businesses thousands of dollars on their utility bills.

Project funding characteristics Stanford University received an ARPA-E award of $2,943,851 as part of the 2012 OPEN competition. The project term was from February 20, 2013, to September 8, 2016. (See Figure C-18.) The technical category for the project is building efficiency.

Technology overview Engineers and architects usually worry about how to insulate so a hot roof does not heat the space below and make the building's air conditioners work even harder. Now, imagine a roof on a hot sunny day that can cool the building. Scientists claimed they could make a sheet of material that would radiate heat right out to space and actually become colder than outside air temperature while in full sun. In 2013, Professor Shanhui Fan at Stanford University published a paper in *Nano Letters*, based on research initiated in 2012, showing that it was theoretically possible to engineer a material that, by reflecting white light, could use the universe as a heat sink, radiating heat out to space and actually becoming cooler than the outside air temperature while in full sun, and helping to cool buildings and other objects. Professor Fan used sold state physics modeling to hypothesize the material structure that would work and to compute its radiation qualities. Just before the paper came out in *Nano Letters*, the ARPA-E 2012 OPEN solicitation was issued, and Fan's group, with the theoretical work under way, proposed to ARPA-E an empirical demonstration of the physics principle involved. The group did not discuss its ideas with ARPA-E.

The timing happened to be right, and the group submitted its proposal. If the group had not received funding from ARPA-E, it probably would have submitted its proposal elsewhere.

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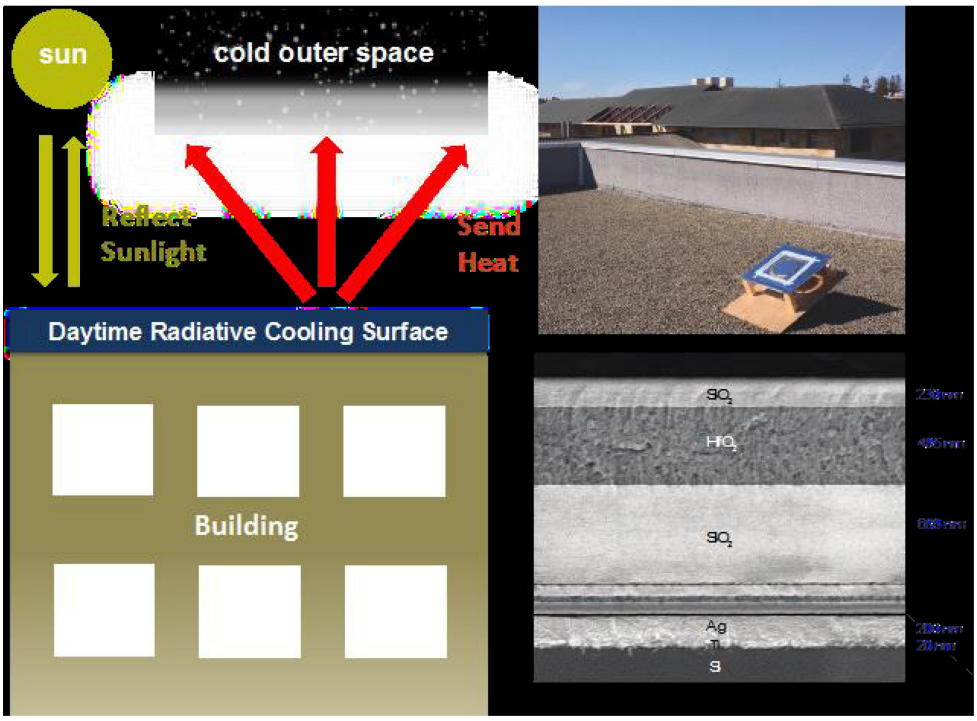

FIGURE C-17 Demonstration of how photonic structures can be used to cool a building, and a picture of an early rooftop test.
SOURCE: http://arpa-e.energy.gov/sites/default/files/documents/files/StanfordRadiativeCooling_OPEN 2012_ExternalImpactSheet_FINAL.pdf.

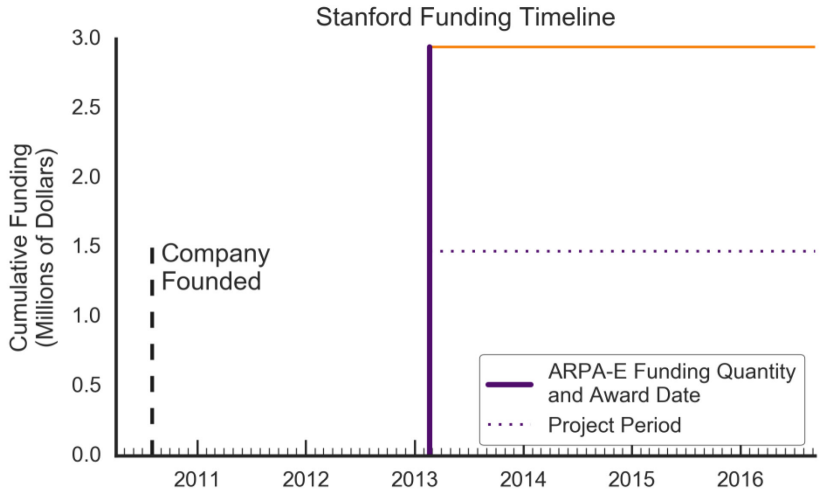

FIGURE C-18 Funding history for Stanford University radiative coolers.
NOTES: Stanford received an ARPA-E award of $2,943,851 as part of the 2012 OPEN competition. The project term was from February 20, 2013, to September 8, 2016. The scales and timeframes in this chart vary and therefore should be compared with caution.
SOURCE: ARPA-E: http://arpa-e.energy.gov/?q=slick-sheet-project/radiative-coolers-rooftops-and-cars.

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Technology-to-market prospects The ARPA-E funding approval (for a 1-year seed project) came at approximately the same time that the theoretical paper was published. When the paper was published, it generated a great deal of interest. DARPA contacted Professor Fan about funding the project, but the group did not pursue the opportunity since it already had the seed money from ARPA-E, and did not think it could scale up quickly enough to manage additional funds at that stage.

ARPA-E emphasized that what was needed was a demonstration in which cooling could be seen. The ARPA-E T2M team also emphasized that significant cost savings would be necessary to achieve commercial viability. Professor Fan's milestone for ARPA-E was to demonstrate a 5 ^{o}C drop in temperature, and the project team was able to achieve this milestone. Shortly after receiving the ARPA-E funds, the team decided to use a deposition technique instead of a lithographic technique to build the material structure, which made it possible to greatly reduce costs. The team carried out the deposition work with a small company (LGA) in Silicon Valley that specializes in this type of work for research purposes. At the end of the 1-year seed project, the team published a paper in *Nature* (November 2014 issue) on the thin films the project had achieved, which demonstrated the predicted cooling effect.

As a consequence of this initial success, the team was able to convince ARPA-E to provide another 2 years of funding. Separate from ARPA-E, as a result of the prominence of the work, Carma Sawyer at EERE commissioned Pacific Northwest National Laboratory to perform a cost analysis of the systemic savings possible with the technology, which proved extremely helpful. Professor Fan expects that if the work had not been funded by ARPA-E, another funder, probably DARPA, would have done so. That said, he believes there was excellent alignment between the group's interests in demonstrating the theoretical work empirically and ARPA-E's interests, and this alignment was extremely helpful in achieving good outcomes.

Outcomes and ARPA-E's role As of February 2016, the project team had generated two invention disclosures with ARPA-E and two U.S. nonprovisional patent applications (ARPA-E, 2016b). It also had published four articles:

- Raman, A., M. Anoma, L. Zhu, E. Rephaeli, and S. Fan. 2014. Passive radiative cooling below ambient air temperature under direct sunlight. *Nature* 515(7528):540-544.
- Zhu, L., A. Raman, and S. Fan. 2013. Color-preserving daytime radiative cooling. *Applied Physics Letters* 103(22):223902.
- Zhu, L., A. Raman, and S. Fan. 2015. Radiative cooling of solar absorbers using a visibly-transparent photonic crystal thermal blackbody. *Proceedings of the National Academy of Sciences of the United States of America* 112(40):12282-12287.
- Zhu, L., A. Raman, K. Wang, M. Anoma, and S. Fan. 2014. Radiative cooling of solar cells. *Optica* 1(1):32-38.

Professor Fan met with the program director every 3 months to provide an update on the project. The program director and the team have provided constructive feedback and advice throughout the project.

Committee assessment The radiative cooling technology translates to practice a concept that was widely thought to be impossible. It is not yet clear why the technology will be important as

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information on preliminary costs and applications appears distant; however, the technology has had the effect of changing all engineering understanding of the limits of practical systems in thermal management. At this stage, it has the potential to be transformational, but it may end up as just a curiosity. The prototypes performed exactly as modeled, and the follow-on research showed significant cost out. However, at its current stage of development, further development, funding, and likely innovative applications will be required for the technology to progress.

The project goals were met as proposed in the initial milestones. While it remains to be seen how impactful the work will be, the project's demonstration that a surprising (erroneously thought to be impossible) process can be accomplished relatively simply, quickly, and inexpensively offers the potential to change building envelope design and other thermal management applications. No one knows whether the process will become inexpensive enough to cool large numbers of roofs, but the simple fact that it is possible may be useful in higher-value applications.

After this case study was completed, ARPA-E released an innovation update stating that, as noted earlier, the Stanford team is scaling its technology to cool water for use in conventional air conditioners and for direct use in the chilled water loops of office buildings, shopping centers, and warehouses,[10] as well as exploring other commercial applications for its technology, including stand-alone systems or use as a complementary component to larger cooling systems. ARPA-E also stated that Stanford's successful demonstration has led other groups to propose similar approaches to passive, radiative cooling for thermoelectric power plants, including projects in ARPA-E's Advanced Research In Dry cooling (ARID) program.[11]

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[10]http://arpa-e.energy.gov/?q=slick-sheet-project/radiative-coolers-rooftops-and-cars (accessed April 26, 2017).
[11]http://arpa-e.energy.gov/?q=slick-sheet-project/radiative-coolers-rooftops-and-cars (accessed April 26, 2017).

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Appendix D

Glossary of Abbreviations and Acronyms

ADEPT	Agile Delivery of Electrical Power Technology
AEP	Advanced Energy Projects Division
ALPHA	Accelerating Low-Cost Plasma Heating and Assembly
America COMPETES Act	America Creating Opportunities to Meaningfully Promote Excellence in Technology, Education, and Science Act of 2007
AMO	Advanced Manufacturing Office
AMPED	Advanced Management and Protection of Energy Storage Devices
API	application programming interface
ARID	Advanced Research in Dry Cooling
ARPA	Advanced Research Projects Agency
ARRA	American Recovery and Reinvestment Act of 2009
BEEST	Batteries for Electrical Energy Storage in Transportation
BEETIT	Building Energy Efficiency Through Innovative Thermal devices
BES	Basic Energy Sciences
BPT	bipolar junction technology
CEO	chief executive officer
CFDA	Catalog of Federal Domestic Assistance
CHARGES	Cycling Hardware to Analyze and Ready Grid-scale Electricity Storage
DARPA	Defense Advanced Research Projects Agency
DELTA	Delivering Efficient Local Thermal Amenities
DNI	direct normal incidence
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DSB	Defense Science Board
EERE	Office of Energy Efficiency and Renewable Energy
ELECTROFUELS	Microorganisms for Liquid Transportation Fuel
ENLITENED	ENergy-efficient Light-wave Integrated Technology Enabling Networks that Enhance Datacenters
EPACT	Energy Policy Act of 2005
FE	Office of Fossil Energy
FOA	Funding Opportunity Announcement

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FOCUS	Full-spectrum Optimized Conversion and Utilization of Sunlight
GAO	U.S. Government Accountability Office
GENI	Green Electricity Network Generation
GENSETS	GENerators for Small Electrical and Thermal Systems
GPS	Global Positioning System
GRID DATA	Generating Realistic Information for the Development of Distribution And Transmission Algorithms
GRIDS	Grid-scale Rampable Intermittent Dispatchable Storage
HEATS	High-Energy Advanced Thermal Storage
HSARPA	Homeland Security Advanced Research Projects Agency
HTML	HyperText Markup Language
IBM	International Business Machines
IDEAS	Innovative Development in Energy-related Applied Science
IMPACCT	Innovative Materials and Processes for Advanced Carbon Capture Technologies
IONICS	Integration and Optimization of Novel Ion-Conducting Solids
IPO	initial public offering
ISAT	Information Science and Technology
KWh	kilowatt hour
LBNL	Lawrence Berkeley National Laboratory
LG	Lucky Goldstar
METALS	Modern Electro/Thermochemical Advances in Light metals Systems
MONITOR	Methane Observation Networks with Innovative Technology to Obtain Reductions
MOSAIC	Micro-scale Optimized Solar-cell Arrays with Integrated Concentration
MOSFET	metal-oxide semiconductor field-effect transistor
MOVE	Methane Opportunities for Vehicular Energy
NAS	National Academy of Sciences
NEXTCAR	NEXT-generation energy technologies for Connected and Automated on-Road vehicles
NICT	National Institute of Information and Communications Technology
NIH	National Institutes of Health
NODES	Network Optimized Distributed Energy Systems
NRC	National Research Council
NSF	National Science Foundation
OE	Office of Electricity
OMB	Office of Management and Budget
PD	program director
PEMD	Program Evaluation and Methodology Division
PETRO	Plants Engineered To Replace Oil
PI	principal investigator
PM	program manager
R&D	research and development
RANGE	Robust Affordable Next Generation Energy storage systems
REACT	Rare Earth Alternatives in Critical Technologies

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REBELS	Reliable Electricity Based on Electrochemical Systems
REFUEL	Renewable Energy to Fuels through Utilization of Energy-dense Liquids
REMOTE	Reducing Emissions using Methanotrophic Organisms for Transportation Energy
RFI	request for information
ROOTS	Rhizosphere Observations Optimizing Terrestrial Sequestration
SBIR/STTR	Small Business Innovation Research/Small Business Technology Transfer
SEC	U.S. Securities and Exchange Commission
SETA	systems engineering and technical assistance
SHIELD	Single-pane Highly Insulating Efficient Lucid Designs
SLIPS	Slippery Liquid-Infused Porous Surfaces
Solar ADEPT	Solar Agile Delivery of Electrical Power Technology
SoT	statement of task
STI	SLIPS Technologies, Inc.
SWITCHES	Strategies for Wide-bandgap, Inexpensive Transistors for Controlling High-Efficiency Systems
T2M	technology-to-market
TERRA	Transportation Energy Resources from Renewable Agriculture
TRANSNET	Traveler Response Architecture using Novel Signaling for Network Efficiency in Transportation
TRL	technology readiness level
USDA	United States Department of Agriculture
USPTO	United States Patent and Trademark Office
VTO	Vehicle Technology Office
WBG	wide-bandgap materials
WOS	Web of Science

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Appendix E

Request for Data from ARPA-E, Input from Other Offices at the Department of Energy, and Agendas for Committee's Public Information Gathering Sessions

This appendix contains three collections of information. The first is the committee's formal request for specific data and information from ARPA-E to make this evaluation possible. The second is written responses from the Department of Energy's Office of Fossil Energy answering questions regarding that office's coordination with ARPA-E and adaption of any ARPA-E practices. The third collection is all of the agendas for public information gathering sessions the committee held during the course of this study.

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September 1, 2015

To:
Ellen Williams, Director
Advanced Research Projects Agency-Energy
U.S. Department of Energy
Washington, D.C.

From:
Pradeep Khosla
Chair of the Committee for the Evaluation of ARPA-E

Dear Director Williams:

Thank you for providing the National Academies of Sciences, Engineering, and Medicine Committee for the Evaluation of ARPA-E with the important information contained in your initial presentations and in the separately provided documents. The Committee appreciates all of the effort and care that you and your staff have already put into this project.

As stated during its last meeting in July 2015, the Committee requires additional information and data in order to fulfill its mandate from Congress to conduct an independent evaluation of the appropriateness and effectiveness of ARPA-E's structure to achieve its mission and the most significant technical accomplishments of the program. We would like to accept your offer to provide additional information and data.

Some of the information the Committee needs includes program and project descriptions that you have already provided or is available through the ARPA-E website. I wish to verify that the Committee has the complete set of information. The Committee and I also recognize that you and your staff are working to complete an internal self-appraisal of the accomplishments and impacts of ARPA-E and plan to provide a presentation at our next meeting in October 2015.

Listed below is the Committee's initial request for additional information. The committee may wish to obtain additional information through the course of its work. In obtaining needed information and data, the Committee and I wish to work with ARPA-E in any way we can – such as by utilizing independent consultants or NAS staff – to minimize the burden on your agency's limited resources while still maintaining our independence. We also want to ensure that there is no compromise of ARPA-E's necessary confidentiality or other legal obligations while fulfilling the Academies' Congressional mandate to conduct an external evaluation. I note that many of these information sources were made available for the Government Accountability Office's review of ARPA-E that was completed in 2012.

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To complete its work, the Committee requires the information and data detailed below. I respectfully request your assistance in helping them obtain these items.

Definitions

The Committee would like to know how ARPA-E:

- Defines 'success' and 'failure' for both programs and projects; and
- Captures and propagates lessons learned from program or project 'successes' and 'failures' institutionally and across program directors and, where appropriate, to other offices and programs within the Department of Energy.

Program Awards, Metrics, and Milestones

The Committee respectfully requests:

- Description of Project Performers – we would like to verify that we have complete descriptions on the full portfolio of both open and focused programs and projects, including information to distinguish whether this is a seedling research effort intended to help develop new focused programs or a "regular" project intended to, eventually, produce a specific commercializable device, the description and location of the performer, and the funding level;
- Access to ARPA-E internal program documents for all focus programs and broad area announcements to date including official Funding Opportunity Announcements, submitted projects, and selection processes;
- For each full application received, detailed project and PI information (e.g., lead-PI, Co-PI and other associated staff and personnel) whether the project was funded or not, including information used to make a fund/don't-fund decision(such as applicant scores);
- For each project funded, a detailed description of milestones and metrics and individual projects' performance against those milestones and metrics;
- A list of instances where project milestones were revised during the course of the project, including descriptions of why ARPA-E and the performer changed the milestones and how those changes impacted the project;
- A list of projects restructured, particularly in response to revising milestones;
- A list of projects terminated, including descriptions of why and how ARPA-E and the performers terminated the projects; and
- A description of the process for terminating or restructuring, including:
    - An explanation of how ARPA-E decides it must discuss restructuring or termination with a project performer; and
    - Whether and how input from outside experts (at dedicated ARPA-E focus program events or the ARPA-E summit, for example) is utilized when making a decision to restructure or terminate a project.

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Project Outputs and Intermediate Outcomes
The Committee respectfully requests:

- Copies of final project reports for all completed projects;
- Lists of journal and other scientific publications derived from ARPA-E funded projects ;
- Lists of patents that derive from ARPA-E funded projects ;
- Data on commercialized outcomes, revenues generated, and follow-on funding acquired by ARPA-E grantees/awardees;
- Data tracked by ARPA-E on performers following completion of individual projects; and
- Graduate students and postdocs funded by ARPA-E programs, and their career trajectories (e.g., academics, industries, startups, or government).

Collaborations and Communities of Interest
The Committee is interested in ARPA-E's work in developing new communities and respectfully requests:

- ARPA-E's description of "new communities" that have been built or enhanced as a result of ARPA-E programs, and evidence to support ARPA-E's role and contribution in forming those communities;
- A description of how these new communities support or have contributed the goals of ARPA-E;
- Programs and agendas from past and planned ARPA-E pre-program workshops, program kickoff meetings, program annual meetings, and annual innovation summits;
- Lists of attendees present at ARPA-E pre-program workshops, program kickoff meetings, program annual meetings, and annual innovation summits;
- Lists of potential collaborations that have derived from, and can be traced to, ARPA-E meetings;
- Proposals (funded/nonfunded) that show evidence of collaboration; and
- Lists of technologies and/or commercialized outcomes, revenues, proposals funded by ARPA-E or other entities, prizes awarded, and submissions by collaborators or communities resulting from or linked to ARPA-E organized meetings.

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Names and Points of Contact
To facilitate contact with necessary individuals and organizations, the Committee respectfully requests:

- List of ARPA-E program directors for consultations or to participate in focus groups;
- Résumés of past and present program directors and deputy directors, as well as personnel within ARPA-E; and
- List of ARPA-E stakeholders to interview including other federal programs or industries that benefit from ARPA-E funded research.

I would appreciate your best efforts to provide the requested information by October 15, 2015. The Committee understands that several of the items above may require further discussion and that some will require careful attention and proper handling to protect confidential information. As I mentioned earlier, the Committee and I stand ready to work with ARPA-E to ensure that protection and note that the National Academies has policies and procedures in place to work with such information, providing the protection that ARPA-E and its applicants require.

I look forward to your response.

Sincerely,

Pradeep Khosla, Chair
Committee for the Evaluation of ARPA-E

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Questions from members of the National Academies Committee on the Evaluation of ARPA-E for

Christopher Smith, Assistant Secretary for Fossil Energy, U. S. DOE

1. Based on your *experience* how would you describe ARPA-E's specific niche and mission and how does ARPA-E's mission relate to DOE's mission and mandate?
   ARPA-E's mission is an important one for the DOE, and covers important space that the applied program offices to not (e.g., gas-to-liquids conversion).
2. Are there aspects of the ARPA-E operations that can (or should) be transferred to DOE? If so, which aspects are transferable?
   No.
3. Has the Office of Fossil Energy adopted operations and procedures from ARPA-E such as the use of funding opportunity announcements (FOA), the methods for awarding of contracts, or the project reporting requirements?
   No. FE has a well-established FOA process, including workshops in advance of new initiatives or programmatic efforts (akin to ARPA-E's approach). These are administered by NETL for FE, which has a large, dedicated staff with deep experience in solicitations, awards, and contracting.
4. Does ARPA-E coordinate with or engage with Office of Fossil Energy? In particular, ARPA-E worked on projects related to carbon capture and sequestration that they describe as being followed-on in work done within your office. To what extent was there coordination between ARPA-E and the Office of Fossil Energy on the carbon capture and sequestration projects?
   Coordination has been poor and partial. Despite several face-to-face discussions between FE and ARPA-E, and interest from both sides in several topics (e.g., advanced carbon capture technology or water treatment and reuse) we have not yet converged. As such, we have had no joint workshops, no joint solicitations, no coordinated launches, and no cooperative roadmapping. While there is benefit in such activities, to date they have not begun.
5. We also note that ARPA-E has funded projects in other areas that might be of interest to your office, such as the advanced laser mechanical drilling technologies of Foro Energy. Do you have any thoughts on how well other ARPA-E projects were developed or the results disseminated to the Office of Fossil Energy?

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There are several areas for ARPA-E's consideration which are currently outside of FEs formal missions space and which would be of great interest to FE. These include:

- ***Advanced technology for drilling and completions***
- ***Advanced technology for water treatment and reuse***
- ***CO2 mineralization and polymerization technology***
- ***CO2 capture and separation from the atmosphere (potentially including direct air capture, application of biochar, and afforestation).***

6. What are your activities related to tech to market?

FE carries technology through to maturation and commercialization. This is carried in different programs in different ways:

- ***Use-Inspired basic programs (Pascal's quadrant), lie in the applied R&D programs of Coal and Oil and Gas. Core R&D in geoscience and Discovery of Carbon Capture Substances (DOCCS) are examples, and fund both National Labs and universities.***
- ***TRL maturation and development lie in those programs as well. These include our conventional granting programs, and commonly involve a mix of academic, industrial, and National Lab partnerships. These grants commonly are designed to move a technology 1-2 TRL levels forward, heading towards market. IP is managed in these efforts, and is commonly held and matured by industrial channel partners.***
- ***FE supports scale-up and demonstration explicitly. These include small pilots (~1 MW), large pilots (10-50 MW), and commercial demonstrations. Almost all of these pilots and demos are done with industrial partners aimed at market deployment.***
- ***Finally, FE has supported and continues to support R&D <u>at commercial sites</u> to assess technical performance in a commercial setting. These include efforts such as the National Carbon Capture Center and the Regional Carbon Sequestration Partnerships.***

In this context, we do not see ARPA-E's efforts as similar to FE's but rather as complementary. They reach a technology ecosystem different from FE's, often including more SME's and a different set of practitioners.

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AGENDA:

Evaluation of ARPA-E Mission and Goals
1st Meeting
May 28, 2015

Room 206
Keck Center, 500 Fifth Street, NW
Washington, DC 20001

May 28, 2015

OPEN SESSION – Open to the Public

12:30 PM Congressional history and intent of evaluation
Hon. Bart Gordon, Chair of House Committee on Science and Technology (former), original sponsor of America COMPETES Act of 2007
Christopher J. King, Staff House Committee on Science and Technology (former)
Adam Rosenberg, Democratic Staff Director, House Committee on Science, Space, and Technology, Energy Subcommittee
Mark Marin, Republican Staff Director, House Committee on Science, Space, and Technology, Energy Subcommittee
Emily Domenech, Republican Staff, House Committee on Science, Space, and Technology, Energy Subcommittee
Lindsay Garcia, General Counsel, Office of Senator Lamar Alexander
John Rivard, Legislative Fellow, Office of Senator Lamar Alexander
Franz Wuerfmannsdobler, Senior Energy Policy Advisor, Office of Senator Coons
Allison Schwier, Congressional Science Fellow, Office of Senator Coons

1:15 PM Sponsor Presentation I: An Overview of ARPA-E
Hon. Ellen Williams, ARPA-E Director

2:15 PM Sponsor Presentation II: ARPA-E Operations
Shane Kosinski, ARPA-E Deputy Director for Operations

3:15 PM Break

3:30 PM Sponsor Presentation III: ARPA-E Programs
Eric Rohlfing, ARPA-E Deputy Director for Technology

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4:30 PM Sponsor Presentation IV: ARPA-E Tech to Market Activities
Dave Henshall, ARPA-E Acting Deputy Director for Commercialization

5:30 PM Break

5:45 PM Establishing ARPA-E
Hon. Arun Majumdar, first ARPA-E Director

6:30 PM Adjourn Open Session. Enter Closed Session.

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AGENDA:

Evaluation of ARPA-E Mission and Goals

2nd Meeting
July 28-29, 2015

Room 206
Keck Center, 500 Fifth Street, NW
Washington, DC 20001

JULY 28, 2015

OPEN SESSION – Open to the Public

8:55 AM Welcome and Introduction
Pradeep Khosla, NAS Committee Chair

9:00 AM Franklin (Lynn) Orr, Undersecretary for Science and Energy

10:00 AM Arati Prabhakar, DARPA Director

11:00 AM Break – End of Open Session for July 28, 2015, Enter Closed Session.

JULY 29, 2015

OPEN SESSION – Open to the Public

8:25 AM Welcome and Introduction
Pradeep Khosla, NRC Panel Chair

8:30 AM Opening comments
Hon. Ellen Williams, ARPA-E Director

8:50 AM Program Directors &Tech to Market Program presentation on GENI (Green Electricity Network Integration)
Tim Heidel & Josh Gould, ARPA-E

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9:35 AM	Program Directors & Tech to Market Program presentation on AMPED (Advanced Management and Protection of Energy Storage Devices) *Pat McGrath & Ryan Umstattd, ARPA-E*
10:20 AM	Break
10:35 AM	PD&T2M Program presentation on METALS (Modern Electro/Thermochemical Advances in Light Metals Systems) *James Klausner, ARPA-E*
11:20 AM	Program Directors &Tech to Market Project presentation on Baldor Electric Co.'s REACT (Rare Earth Alternatives in Critical Technologies) project *Pat McGrath & Kacy Gerst, ARPA-E*
11:40 AM	Program Directors &Tech to Market Project presentation on Arizona State University's FOCUS (Full-Spectrum Optimized Conversion and Utilization of Sunlight) project *Eric Schiff & James Zahler, ARPA-E*
12:00 PM	Additional Q&As and concluding remarks
12:30 PM	Adjourn Open Session, Enter Closed Session.

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AGENDA:

Evaluation of ARPA-E Mission and Goals

3rd Meeting
October 29-30, 2015

Room 103
Keck Center, 500 Fifth Street, NW
Washington, DC 20001

OCTOBER 29, 2015

OPEN SESSION – Open to the Public

1:00 PM Welcome and Introduction
Pradeep Khosla, NAS Committee Chair

1:05 PM Assessment of ARPA-E's impacts and tracking of future outcomes
Hon. Ellen Williams, ARPA-E Director

2:35 PM Perspectives from ARPA-E Alumnus - Sonic Joule, LLC
Robert Keolian, President, Sonic Joule LLC

3:20 PM Break

3:35 PM Perspectives from ARPA-E Alumnus – ForoEnergy
Joel Moxley, Founder & EVP Business Development

4:20 PM GAO Staff – results and methodology used in 2012 GAO evaluation of ARPA-E
GAO Staff Analyst

5:10 PM Adjourn Open Session, Enter Closed Session.

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AGENDA:

Evaluation of ARPA-E Mission and Goals

4th Meeting
December 8-9, 2015

Board Room
Beckman Center, 100 Academy Drive
Irvine, CA 92617

DECEMBER 8, 2015

OPEN SESSION – Open to the Public

10:00 AM Perspectives from ARPA-E Alumnus Program Director
Hon. David Danielson, Assistant Secretary for Energy Efficiency and Renewable Energy

11:00 AM Adjourn Open Session

CLOSED SESSION – BECKMAN CENTER BOARD ROOM

11:15 AM Enter closed session

OPEN SESSION – Open to the Public

1:00 PM Welcome and Introduction
Pradeep Khosla, NAS Committee Chair

1:05 PM Perspectives of the former ARPA-E Director
Arun Majumdar

2:05 PM Perspectives from ARPA-E Alumnus Program Directors
Ilan Gur, Jonathan Burbaum, Howard Branz, Dane Boysen

2:45 PM Q&A and Discussion with ARPA-E Alumnus Program Directors
Ilan Gur, Jonathan Burbaum, Howard Branz, Dane Boysen

3:15 PM Break

3:30 PM Perspective on Government Agencies for Technology Innovation
David Mowery and Shane Greenstein

4:30 PM Adjourn Open Session

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AGENDA:

Evaluation of ARPA-E Mission and Goals

5th Meeting
February 29 – March 1, 2016

FEBRUARY 29, 2016

OPEN SESSION

3:00 PM	Committee members visit ARPA-E Technology Innovation Summit
7:00 PM	Depart Summit and Adjourn Open Session, Enter Closed Session.

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Appendix F

Consultants' Reports of Data Analysis

The committee engaged and directed independent consultants to analyze data and information provided by ARPA-E and available in the public domain as part of its evaluation of ARPA-E. Those consultants produced two working papers detailing the results of their analysis. The committee utilized both working papers in its deliberations and analysis. The first, Goldstein and Kearney (2016), analyzes internally-generated data from ARPA-E. The second, Goldstein (2016), analyzes publically available data. These working papers are available on the NAP website at: https://www.nap.edu/catalog/24778 under the Resources tab.

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