U.S. DEPARTMENT OF ENERGY

ARPA-E Strategic Vision Roadmap

Report to Congress
August 2022

United States Department of Energy
Washington, DC 20585

Message from the Acting Director

The Advanced Research Projects Agency-Energy (ARPA-E) catalyzes and accelerates disruptive energy technologies that will enhance the economic and energy security of United States. It achieves this through the development of transformational technologies that: reduce the America's dependence on energy imports; reduce energy related emissions; improve energy efficiency across all sectors of the economy; provide transformative solutions to improve the management, clean-up, and disposal of radioactive waste and spent nuclear fuel; and improve the resilience, reliability, and security of infrastructure to produce, deliver, and store energy. This helps to ensure that the United States maintains a technological lead in developing and deploying advanced energy technologies. ARPA-E advances high-risk, high-impact energy technologies that are too early for private sector investment, with performance goals driven by both technical and market needs. It is important to note that the Agency's missions are not mutually exclusive; programs and projects supported by ARPA-E often address multiple mission areas to accelerate creation of transformative energy technologies. These technologies allow for the development of safe and responsible domestic energy and promote the Administration's goal of U.S. global leadership in the clean energy economy, including a focus on manufacturing in the United States.

Pursuant to requirements under 42 U.S.C. § 16538(h)(2), this report is being provided to the following Members of Congress:

- **The Honorable Joe Manchin III**
  Chairman, Senate Committee on Energy and Natural Resources
- **The Honorable John Barrasso**
  Ranking Member, Senate Committee on Energy and Natural Resources
- **The Honorable Mazie K. Hirono**
  Chair, Subcommittee on Energy
  Senate Committee on Energy and Natural Resources
- **The Honorable John Hoeven**
  Ranking Member, Subcommittee on Energy
  Senate Committee on Energy and Natural Resources
- **The Honorable Frank Pallone, Jr.**
  Chairman, House Committee on Energy and Commerce
- **The Honorable Cathy McMorris Rodgers**
  Ranking Member, House Committee on Energy and Commerce
- **Honorable Eddie Bernice Johnson**
  Chairwoman, House Committee on Science, Space, and Technology
- **The Honorable Frank Lucas**
  Ranking Member, House Committee on Science, Space, and Technology

- **The Honorable Jamaal Bowman**
  Chair, Subcommittee on Energy
  House Committee on Science, Space, and Technology
- **The Honorable Randy Weber**
  Ranking Member, Subcommittee on Energy
  House Committee on Science, Space, and Technology
- **The Honorable Patrick Leahy**
  Chairman, Senate Committee on Appropriations
- **The Honorable Richard Shelby**
  Vice Chairman, Senate Committee on Appropriations
- **The Honorable Dianne Feinstein**
  Chairman, Subcommittee on Energy and Water Development
  Senate Committee on Appropriations
- **The Honorable John Kennedy**
  Ranking Member, Subcommittee on Energy and Water Development
  Senate Committee on Appropriations
- **The Honorable Rosa DeLauro**
  Chairwoman, House Committee on Appropriations
- **The Honorable Kay Granger**
  Ranking Member, House Committee on Appropriations
- **The Honorable Marcy Kaptur**
  Chairwoman, Subcommittee on Energy and Water Development
  House Committee on Appropriations
- **The Honorable Mike Simpson**
  Ranking Member, Subcommittee on Energy and Water Development
  House Committee on Appropriations

If you have questions or need additional information, please contact me or Ms. Katie Donley, Deputy Director of External Affairs, Office of the Chief Financial Officer, at 202-586-0176; Mr. Michael Harris, Legislative Affairs Advisor for House Affairs; or Ms. Rebecca Ward, Deputy Assistant Secretary for Senate Affairs, Office of Congressional and Intergovernmental Affairs, at 202-586-5450.

Sincerely,

Dr. Jennifer Gerbi
Acting Director
Advanced Research Projects Agency-Energy (ARPA-E)

Executive Summary

Advanced Research Projects Agency-Energy (ARPA-E) is pleased to present this Strategic Vision Roadmap, which will help guide ARPA-E's technology investments for Fiscal Years 2022-2025.

ARPA-E funds technologies that have the potential to change the way we obtain, store, and use energy. ARPA-E's mission is to advance energy innovations that will create a more secure, affordable, and sustainable energy future for the entire United States (U.S.).

ARPA-E focuses on early-stage energy technologies that can be meaningfully advanced with modest funding over a defined time period. ARPA-E's rigorous program design, competitive project selection process, and hands-on engagement provide America's energy researchers with funding, technical assistance, and market awareness. ARPA-E also avoids duplication with work pursued by industry, other Federal agencies, and other Department of Energy (DOE) applied research and development (R&D) program offices, while enabling and encouraging coordination and communication with these other entities.

As of January 2022, ARPA-E projects have formed 129 companies, 268 projects have partnered with other government agencies for further development, and an ever-increasing number of technologies have been incorporated into products sold in the market. ARPA-E-funded technologies have resulted in 829 patents issued by the U.S. Patent and Trademark Office, and so far, 285 licenses have been issued for ARPA-E technology. Additionally, 185 project teams and their ARPA-E-funded technologies have attracted more than $9.87 billion in private-sector follow-on funding.

ARPA-E continues to focus on providing awardees with practical training and critical business information as part of the agency's Technology-to-Market program. This support equips performers with a clear understanding of market needs to guide technical development and help projects succeed in the marketplace.

This Roadmap presents ARPA-E's plans to:

- Continue catalyzing and accelerating disruptive energy technologies that enhance the economic and energy security of the United States. Six examples of potential future ARPA-E "technology investment areas" are presented. These technologies – and others to be identified through the rigorous processes described below – allow for the development of safe and responsible domestic energy and promote the administration's

goal of U.S. global leadership in the clean energy economy, including a focus on manufacturing in the United States.

- Achieve ARPA-E's statutorily-established goals of:
    - reducing America's dependence on energy imports;
    - reducing energy related emissions;
    - improving energy efficiency across all sectors of the economy;
    - providing transformative solutions to improve the management, clean-up, and disposal of radioactive waste and spent nuclear fuel;
    - improving the resilience, reliability, and security of infrastructure to produce, deliver, and store energy; and
    - ensuring the United States maintains a technological lead in developing and deploying advanced energy technologies.

- Continue to advance high-risk, high-impact energy technologies that are too early for private sector investment, with performance goals driven by both technical and market needs.

- Maintain the use of its successful model of streamlined, agile program development and highly-competitive awards processes, selecting projects through "focused" and "open" programs, quickly and effectively leveraging new scientific discoveries and market developments.

- Continue to engage with academia, small and large businesses, other DOE program offices, and other government agencies to facilitate relationships necessary for awardees to move to the next stage of their project development; and

- Track and evaluate the success of awardee technologies after their participation in research programs in order to demonstrate the transformative effects of ARPA-E's investments more clearly.

ARPA-E STRATEGIC VISION ROADMAP

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I. Legislative Language

This report is in response to the requirements set forth in ARPA-E's authorizing statute, 42 U.S.C. § 16538, as amended in 2020 by Public Law 116-260, sec. 10001(d), wherein it is stated:

"…the Director shall provide to the relevant authorizing and appropriations committees of Congress a roadmap describing the strategic vision that ARPA-E will use to guide the choices of ARPA-E for future technology investments over the following 4 fiscal years."

See 42 U.S.C. § 16538(h)(2).

II. Overview and History

ARPA-E catalyzes transformational energy technologies that could create a more secure and affordable American future by advancing high-potential, high-impact energy technologies that are too early for private sector or other DOE applied R&D investment.

ARPA-E was established by the America COMPETES Act of 2007 following a recommendation by the National Academies in a report entitled Rising Above the Gathering Storm.[1] As of September 2021, ARPA-E has provided $3 billion in funding to 1,294 projects across 49 states. These projects have been selected via more than 60 focused programs and five open solicitations. Approximately 30 percent of funding for projects has gone to small businesses, 43 percent to universities, 14 percent to large businesses, 9 percent to National Laboratories, and 4 percent to non-profits. This distribution is reflective of both the applications received by the Agency and of the types of multi-disciplinary, multi-institutional teams that are most effective in developing transformative energy technologies.

III. ARPA-E Model

ARPA-E is modeled after the successful Defense Advanced Research Projects Agency (DARPA) and has created a unique, nimble, and adaptive structure that allows the Agency to quickly develop and execute programs, recruit a highly talented and experienced technical team, and provide awardees with technical assistance and market awareness to help projects succeed.

At the core of the ARPA-E model is the team, particularly the Agency's program directors and technology-to-market advisors. ARPA-E program directors drive the agency, determining

[1] National Academy of Sciences, National Academy of Engineering, and Institute of Medicine. 2007. *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*. Washington, DC: The National Academies Press. https://doi.org/10.17226/11463

answers to “what problem should be solved, and why,” and “what should that solution look like to achieve impact.” These answers lead, via much pressure testing and outreach, to metric-driven focused programs that create carefully researched funding solicitations. Program directors also provide awardees with technical guidance that combines scientific expertise and real-world experience, while ARPA-E technology-to-market advisors supply awardees with critical business insight and strategies to move technologies toward the market. ARPA-E recruits program directors and technology-to-market advisors from diverse backgrounds including academia, industry, and National Laboratories. These individuals are leaders in their respective fields and come to ARPA-E for limited three-to-five-year terms. These limited terms instill a sense of urgency to succeed and regularly provide a fresh perspective on technologies and current market conditions. This term-limited approach also helps enable a collaborative and competition-free culture, which is of extreme importance to maintaining an environment where all perspectives and opinions are welcomed and value.

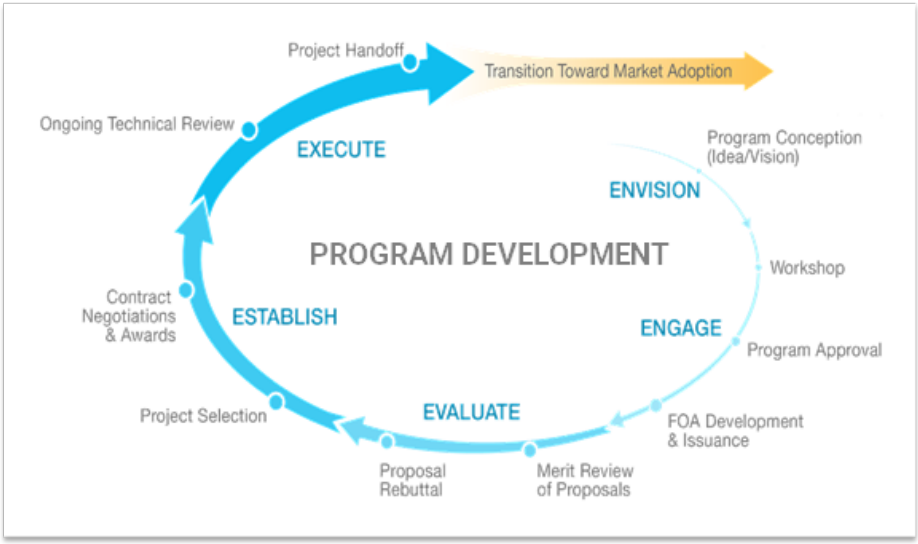
To ensure that program directors are able to maximize the impact of a limited term and give ARPA-E the agility to move into new technical areas and quickly react to changes in the market, ARPA-E has streamlined the program development and awards process. ARPA-E awards are selected through two models: “focused” programs, which are developed by program directors to address a specific energy challenge; and “open” solicitations, which seek applications for any idea that has the potential to produce game-changing breakthroughs in energy technology. ARPA-E encourages interdisciplinary thinking for both “open” solicitations and “focused” programs by recommending the use of a diverse combination of skills and partners that can approach challenges in new ways. Forming new communities to solve problems is a hallmark of our program development process.

ARPA-E “focused” programs provide a unique bridge from basic science to early-stage technology. These programs draw from the latest scientific discoveries and envision a viable path to commercial implementation through firm grounding in the economic realities and changing dynamics of the marketplace. For example, ARPA-E’s Rapid Encapsulation of Pipelines Avoiding Intensive Replacement (REPAIR) program was created to develop technologies to eliminate methane leaks from legacy distribution pipes in-situ, avoiding the need for digging or service interruptions. The Duration Addition to electricitY Storage (DAYS) program was created to develop novel energy storage systems that provide power to the grid in the 10 to100-hour timeframe, enabling greater renewable penetration, increased resilience, and improved performance. ARPA-E’s Performance-based Energy Resource Feedback, Optimization, and Risk Management (PERFORM) program was developed to create innovative management systems for the electric grid that represent the relative delivery risk of each asset, like wind farms or power plants, and balance the collective risk of all assets across the grid resulting in improved

capacity and operation. Additionally, ARPA-E's new Seeding Critical Advances for Leading Energy technologies with Untapped Potential (SCALEUP) program addresses the technology "scaling gap", by supporting teams in their efforts to translate technical performance achieved at the lab-and bench-scale to commercially viable versions of the technology in order to reduce risk and enable the technology to move forward and make an impact on the Agency's mission.

The concept for a new "focused" program is developed through engagement with diverse science and technology communities, including some that may not have traditionally been involved in the topic area, engagement with the entire value chain for the proposed technology including the end users, and by examining lessons learned from current and former ARPA-E programs and projects. The program development cycle also involves careful comparison of ongoing research and development efforts in other DOE program offices, other governmental agencies and Departments, and industry. For instance, the Galvanizing Advances in Market-Aligned Fusion for an Overabundance of Watts (GAMOW) program, which is supporting innovative R&D in fusion-energy subsystems and cross-cutting areas to enable commercially attractive fusion energy, has been closely coordinated with industry stakeholders and the DOE Office of Science–Fusion Energy Sciences, which is also jointly funding the program.

The ARPA-E program development cycle is primarily about identifying gaps where high-impact, high-potential investment by ARPA-E could lead to transformational technologies enabling entirely new ways to generate, store, and use energy. New programs are carefully constructed by program directors with the assistance of their teams (including a tech-to-market advisor), working in an environment that encourages constructive criticism and where every aspect of a proposed program is intensely scrutinized for technical and economic viability, as well as impact on ARPA-E's mission.



During program development, ARPA-E program directors identify new opportunities and innovative ways to tackle some of America's toughest new and existing energy issues. ARPA-E program directors and tech-to-market advisors complete a deep-dive into the program's subject matter to identify strategic pathways for program development. The ARPA-E team engages with ARPA-E leadership and colleagues for internal debate, considers lessons learned from previous programs, identifies any overlap research with other Departmental offices, conducts external expert interviews, reviews market data, and creates a market analysis of the program's commercial viability. ARPA-E's rigorous program design and open discussion between stakeholders and other Departmental programs aim to refine the scope of each ARPA-E program to avoid duplication of research and resources.[2]

ARPA-E also ensures that potentially transformational ideas outside the scope of existing "focused" programs are not lost by periodically utilizing "open" funding opportunity announcements (FOA). Projects selected under the "open" solicitations pursue novel approaches to energy innovation, and work to meet technical needs not addressed by other ARPA-E programs, other parts of DOE, other Federal agencies, or the private sector.

ARPA-E's model to evaluate applications considers a mix of quantitative and qualitative criteria. Concept Papers are primarily evaluated by internal and external reviewers based on the Merit Review Criteria specific to a given FOA. Compliant and responsive Full Applications are evaluated by subject matter experts against the technical merit review criteria described in the FOA. ARPA-E may also use Program Policy Factors as part of its evaluations and selection decisions, which are broad policy considerations determined by agency needs and priorities.

In 2018, ARPA-E created the Solicitation on Topics Informing New Program Areas, publicly known as "Exploratory Topics (ETs)" which enables ARPA-E to quickly move smaller efforts forward in order to support new or existing focused programs (for example, with specific novel instruments for technical measurements, validation techniques, or studies) or to investigate potential new seedling program areas while highlighting energy challenges of critical interest to the competitiveness and security of the United States. These ETs cover a wide range of technical areas to encourage the submission of the most innovative and unconventional ideas in energy technology that, if successful, could establish new program areas for ARPA-E, or complement the current portfolio of ARPA-E programs.

[2] United States Government Accountability Office (GAO). 2022. *Advanced Research Projects Agency-Energy: Agency Has Practices for Avoiding Duplication and Involving Stakeholders in the Development of Research Programs (GAO-22-104775)*. Washington, DC. https://www.gao.gov/products/gao-22-104775.

A key component of the ARPA-E model is hands-on engagement with awardees. Each ARPA-E project includes clearly defined technical and commercial milestones that awardees are required to meet throughout the life of a project. Program directors work closely with each awardee, through regular meetings and on-site visits, to ensure that milestones are being achieved in a timely fashion. When a project is not achieving the goals of the program, ARPA-E works with the awardee to rectify the issue or, in cases where the issue cannot be corrected, ARPA-E discontinues funding for the project. To ensure the agility and efficiency of ARPA-E's hands-on engagement with awardees, ARPA-E has in-house legal, procurement, and contracting staff, co-located with the program directors to provide direct access and timely communication.

The final element of the ARPA-E model is the Technology-to-Market Program, ARPA-E Technology-to-Market Program provides awardees with practical training and critical business information to equip project teams with a clear understanding of market needs, in order to guide technical development and help projects succeed. Awardees are required to provide a Technology-to-Market Plan at the beginning of their project and work closely with ARPA-E's Technology-to-Market Advisors to further refine the Plan and their overall commercialization strategy throughout the project, developing strategies to move projects toward the marketplace. In addition, ARPA-E facilitates relationships with investors, government agencies, small and large companies, and other organizations that are necessary to move technologies to the next stage of development.

In 2020, ARPA-E created the SCALEUP program to assist promising ARPA-E-funded projects in addressing the "scaling gap" and retiring technical risks associated with product development, manufacturing, and deployment in real energy systems. SCALEUP is a first-of-its-kind initiative for ARPA-E, supporting the scaling of high-risk and potentially disruptive new technologies across the full spectrum of energy applications. The goal of the program is to support teams in their efforts to translate the technical performance achieved at the lab-and bench-scale to commercially viable versions of the technology. This allows ARPA-E teams to substantially build upon their earlier innovations, enabling a path to market that maximizes commercial impact and new energy technology adoption.

The success of ARPA-E programs and projects will ultimately be measured by impact in the marketplace. As the projects ARPA-E funds seek to generate transformational energy technologies that do not exist today, ARPA-E looks at various metrics to measure progress towards eventual market adoption. The primary metrics are the individual project and program milestones, which are reviewed quarterly, while more broadly, technical success is measured by indicators such as patents and publications. Most importantly, ARPA-E gauges success by the creation of communities and project handoffs, including the formation of new companies

and the ability of those companies to secure additional development funding from public or private investors.

ARPA-E analyses and catalogues some of the Agency's most successful projects through its which explore a sampling of individual projects and their achievements and noted on our website under impacts.

One transformational technology came from Transportation Energy Resources from Renewable Agriculture (TERRA) program's Purdue University project titled "Automated Sorghum Phenotyping and Trait Development Platform." As of December 2017, the project has generated five invention disclosures to ARPA-E. One U.S. Patent and Trademark Office (PTO) patent application has been filed on the disclosed inventions. The project has also published the scientific underpinnings of this technology five times in open literature and presented at conferences all over the work.

Many ARPA-E funded projects have also spun off to form new start-up companies. For example, Zap Energy was founded in 2017 as a spinout from the FuZE (Fusion Z-pinch Experiment) research team at the University of Washington. Prior to spinning out, the FuZE team received funding from several U.S. Department of Energy programs, dating back to 1998. While the FuZE team had been working on the science of plasma stabilization of their fusion concept for decades, ARPA-E began supporting the FuZE team in 2015 on advancing the fusion performance of their concept, as part of the Accelerating Low-Cost Plasma Heating and Assembly (ALPHA) program. This would later lead to the founding of Zap Energy. The circular ARPA-E Model and marketplace success metrics provide ARPA-E the ability to gauge the success of our projects by highlighting accomplishments in new companies or follow-on funding, as well as reviewing lessons learned to continually develop new, innovative ideas and processes for disruptive technology.

As of January 2022, 185 of ARPA-E projects have attracted more than $9.87billion in private sector follow-on funding and 268 projects have partnered with other government agencies for further development. These indicators demonstrate that ARPA-E's approach to selecting, funding, and actively managing early-stage energy R&D continues to pay off, advancing the state of the art in energy science and engineering and defining new opportunities for commercialization of advanced energy technologies.

IV. Strategic Vision & Mission Implementation

The mission of ARPA-E is to catalyze and accelerate the creation of transformational energy technologies by making investments in the early stages of development. By definition, the Agency is not bound by traditional technology development roadmaps. To the contrary, ARPA-E works "off roadmap" to quickly leverage new scientific breakthroughs and market developments. ARPA-E explores uncharted territories of energy technology and the intersections of those territories in order to create options for entirely new paths to accelerate the pace of innovation. ARPA-E uses a set of simple, but not always easily answered, questions to frame new programs (see "ARPA-E Program Framing Questions" below). The most critical question is the simplest of all: "If it works, will it matter?" This is an overarching principle that guides all of ARPA-E's efforts.

ARPA-E Program Framing Questions

1. What are you trying to do? Articulate your objectives using absolutely no jargon. (I.e., what is the problem, and why is it hard?)
2. How is it done today, and what are the limits of current practice?
3. What is new in your approach and why do you think it will be successful?
4. Who cares?
5. If you are successful, what difference will it make? (I.e., what is the impact, and how will it be measured?)
6. What are the risks?
7. How much will it cost? How long will it take?
8. What are the mid-term and final "exams" to check for success?

Adapted from the DARPA Heilmeier questions

ARPA-E engages strategically with other Department of Energy agencies to coordinate R&D as well as program development and review efforts. During the Program Development Cycle, ARPA-E will solicit constructive feedback technical experts from various Departmental offices to further refine the program scope and interest areas and participate in working groups to . ARPA-E participates in Department-wide working groups to collaboratively identify new clean energy solutions.

Additionally, ARPA-E coordinates funding and award selections with other Departmental offices. In March 2021, DOE announced $110 million to diverse small businesses working on scientific, clean energy, and climate solutions for the American people. The awards announced

are administered by DOE's Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs, which were established to encourage diverse communities to participate in technological innovation, as well as create a bridge between DOE-supported science breakthroughs and viable products and services for the commercial market. The funding came through DOE's Office of Science (SC), as well as ARPA-E. The 102 projects are pursuing technological solutions in various areas, including advanced manufacturing of wind turbines and batteries, new instruments for atmospheric measurement, and particle accelerator technologies that can power next-generation scientific discoveries.

ARPA-E will continue our close, strategic coordination with other DOE offices to advance the Department's mission to ensure America's security and prosperity by addressing its energy, environmental, and nuclear challenges through transformative science and technology solutions.

V. Potential Energy Technology Investment Areas

The inherent non-roadmap, bottom-up approach makes it impossible to predict in detail the specific technologies that will garner future investment. Nevertheless, ARPA-E envisions building from existing learning, often in a nonlinear and unexpected fashion, including the following broad areas:

Methane Mitigation and Alternative Fuels: Natural gas combustion currently accounts for over 30 percent of the total energy generation in the U.S. It is valuable for managing residential winter peaking thermal energy demands and supporting variable renewable electricity generation. Natural gas is also a potent greenhouse gas. While there are ongoing public and private efforts to deploy known solutions, new technologies are needed to address all methane emissions, including from sources such as a leaking natural gas distribution infrastructure, coal mine venting and oil and gas wells (both active and abandoned), and even agriculture. In the longer term, it would be ideal to shift to efficient electric uses when possible, and then focus on replacing some methane uses with alternatives that could be "drop-in" replacements, be derived from renewable energy, and have a low (or even negative) carbon footprint. There are significant efforts in the U.S. and globally to develop such alternate liquid and gaseous fuels as energy carriers. Novel routes to gaseous fuels such as (but not limited to) hydrogen would create opportunities to leverage the country's extensive gas infrastructure and meet climate objectives. Decarbonizing hard to electrify portions of the transportation sector such as maritime and aviation will also require alternate fuels, and energy density and handling of

those fuels will also be of key importance. Challenges in producing such fuels lies in finding innovative ways to source sustainable feedstock (agricultural and other) and efficiently generating useful fuel compounds from those feedstocks. Sourcing and using carbon dioxide directly from the air or point sources could avoid land use requirements from state-of-the-art biofuel replacements. New conversion and supply chain efficiency technologies could improve the sustainability of biofuel production, utilizing abundant domestic biomass resources, and could offer both an enhancement in energy security and a significant step forward in reducing greenhouse gas emissions from vehicles. Advances in engineering, chemistry, catalysis, biotechnology, and refining will identify and develop innovative carbon neutral fuel synthesis routes from increasingly sustainable feedstocks.

Alternate Generation: Large scale, dispatchable, zero-carbon electricity is crucial to reach our climate goals while enabling energy security for the country. Nuclear fission and fusion power are both critically important to this end, and each has significant challenges. The development of advanced fission reactors is on track to provide a wide range of options in terms of modularity, power level, and deployment options. The pace of advanced reactor deployments depends on a number of factors, including the economics of nuclear power and the acceptable disposition of used nuclear fuel. ARPA-E has made significant contributions to the economics and continued safety of nuclear power by supporting innovations to reduce both capital expenditures and operation and maintenance costs through new materials, new construction technologies, and preventative maintenance via digital twins. ARPA-E is also proactively addressing the backend of advanced reactor fuel cycles to mitigate the impact of the final disposition of used nuclear fuel. Fusion may be another option for clean, dispatchable generation, and the multi-decadal pursuit of fusion energy has reached an inflection point with both magnetic and inertial fusion on the cusp of demonstrating scientific energy breakeven (i.e., fusion energy exceeding external energy applied to the fuel), representing a mature physics understanding of these phenomena. In addition, advances in enabling materials and technologies, largely driven by other disciplines and applications (e.g., high-temperature superconductors, advanced manufacturing, sophisticated active feedback control, energy conversion devices) are enabling new, less-complex, lower-cost fusion designs that were not possible even a decade ago. ARPA-E's fusion programs aim to provide targeted R&D opportunities to bring these advances together to greatly accelerate the pace toward timely, cost-competitive, commercially viable fusion energy. The multi-disciplinary teams that ARPA-E fosters are ideal to bring together the most advanced tools needed to rapidly enable both advanced fission and fusion in a time frame relevant to mitigate climate change.

Energy Infrastructure and Integration: Tying all of our desired energy technologies together in a functional way that is also robust, resilient, and secure is perhaps the greatest technical

challenge we face. Improvements in both hardware and software (e.g., energy conversion devices at both small and large scales, novel sensors, grid optimization, etc.) will be key enabling technologies toward this end. The very way our infrastructure is controlled, including the grid and all assets tied to it, must be improved. ARPA-E has invested in building the innovative new components that need to be integrated into larger systems to achieve full impact and now sees a broad opportunity in the combination of sensor technology, informatics, and system integration. ARPA-E has had multiple programs (including our first ever competitions) regarding grid control and operations. This space will need a significant amount of continued attention in order to reap the benefits of all of the novel technologies that are being developed today across the energy generation and usage space.

Carbon Removal Technologies: Meeting global climate targets requires not only reducing carbon emissions but enabling a sufficient carbon dioxide removal and sequestration or utilization capacity at an extremely large scale. Realizing a new carbon economy – one that removes, efficiently uses, and stores more carbon than it emits – will require new technologies to provide carbon-based products in a carbon neutral or carbon negative fashion while simultaneously establishing large scale, low cost, and energy efficient negative emissions pathways. Novel carbon-neutral and -negative materials and products could be used in everything from fuels and chemicals to our built environment. These efforts and resulting advanced technologies will enable the sustainable production of necessary carbon-based products while offering low cost and energy efficient pathways for removing and utilizing carbon.

Efficient Computation and Data Processing: Energy using applications that are 'invisible' to the user can be some of the most difficult areas to mitigate. The number of data centers, large and small, handling our ever-expanding amount of information is increasing at a staggering pace, even outside of aggressively energy-hungry technologies such as blockchain currency. Improving the energy utilization and efficiency of data centers will be crucial. Ways to validate the amount of energy required for computation will be essential, and algorithms optimized for energy-efficiency will become increasingly important. As the number of sensors, especially data-heavy sensors utilizing 5G, expand (as is predicted with autonomous vehicles), attention must be paid to the energy usage of these data gathering and computation processes. For example, a reality may arise in which autonomous vehicles use more energy in sensors, data transfer, and computation for controls than the car itself needs to move, and the strategies to address this potential scenario should be investigated now.

Energy Storage: High performance energy storage continues to be a crucial component for the decarbonization of U.S. transportation and electricity sectors. ARPA-E has made significant

investments in electrical energy storage for both applications, and these programs have built new communities of scientists and engineers that are approaching the challenge of energy storage in new and exciting ways. ARPA-E continues to explore potential new program areas that push the limits of energy storage cost and performance, leveraging new insights from commercial stakeholders on what is required to have a disruptive impact on our energy system. For stationary applications (grid, microgrid, or off-grid), there is a growing realization that energy storage capital costs must be substantially reduced beyond those of today's state-of-the-art lithium-ion batteries to enable widespread deployment. ARPA-E has taken a technology-neutral approach to this challenge, considering new battery technologies as well as novel thermal, chemical, geomechanical, thermophotovoltaic, and other forms of electrochemical storage. New energy storage companies have formed as a result of ARPA-E funding and are advancing technologies to the market, and we see needs in this area continuing to expand.

VI. Conclusion

Over the next four fiscal years, ARPA-E will continue to catalyze and accelerate the development of transformational energy technologies that could enable a more secure and affordable energy future in America. ARPA-E will maintain the use of its successful model to select projects through "focused" and "open" programs, quickly and effectively leveraging new scientific discoveries and market developments. ARPA-E will also continue to engage with academia, small and large businesses, other DOE program offices, and other government agencies to facilitate relationships necessary for awardees to move to the next stage of their project development. In addition, ARPA-E will track and evaluate the success of awardee technologies after their participation in a funding program in order to assess the transformative effects of ARPA-E's investments more clearly.

VII. Appendix I: ARPA-E Programs

Table 1 on the following page summarizes ARPA-E's programs as of March 2022. Additional information related to these projects is on ARPA-E's website: http://arpa-e.energy.gov.

TABLE 1: ARPA-E PROGRAMS TO DATE

FUNDING YEAR	PROGRAM NAME	NUMBER OF PROJECTS	FUNDING AMOUNT ($ Million)[3]
2009	OPEN 2009	41	$174

[3] Funding levels shown in this chart are current as of September 2021 unless otherwise stated. All counts and funding amounts reflect information at the time of selection. Final number of projects and funding amounts are subject to change based on award negotiations.

TABLE 1: ARPA-E PROGRAMS TO DATE			
FUNDING YEAR	**PROGRAM NAME**	**NUMBER OF PROJECTS**	**FUNDING AMOUNT ($ Million)[3]**
2010	Batteries for Electrical Energy Storage in Transportation (BEEST)	12	$38
2010	Innovative Materials and Processes for Advanced Carbon Capture Technologies (IMPACCT)	15	$40
2010	Electrofuels	13	$48
2010	Agile Delivery of Electrical Power Technology (ADEPT)	14	$38
2010	Building Energy Efficiency Through Innovative Thermodevices (BEETIT)	17	$38
2011	Grid-Scale Rampable Intermittent Dispatchable Storage (GRIDS)	15	$40
2011	Plants Engineered To Replace Oil (PETRO)	10	$56
2011	High Energy Advanced Thermal Storage (HEATS)	15	$37
2011	Rare Earth Alternatives in Critical Technologies (REACT)	14	$39
2011	Green Electricity Network Integration (GENI)	15	$43
2011	Solar Agile Delivery of Electrical Power Technology (Solar ADEPT)	7	$12
2012	Methane Opportunities for Vehicular Energy (MOVE)	13	$42
2012	Advanced Management and Protection of Energy Storage Devices (AMPED)	15	$34
2012	OPEN 2012	66	$171
2013	Innovative Development in Energy-related Applied Science (IDEAS)	59	$28
2013	Robust Affordable Next Generation Energy Storage Systems (RANGE)	22	$45
2013	Reducing Emissions using Methanotrophic Organisms for Transportation Energy (REMOTE)	16	$48
2013	Modern Electro/Thermochemical Advancements for Light metals Systems (METALS)	19	$45
2013	Strategies for Wide Bandgap, Inexpensive Transistors for Controlling High Efficiency Systems (SWITCHES) & SBIR/STTR	14	$36
2014	Full-Spectrum Optimized Conversion and Utilization of Sunlight (FOCUS)	14	$35
2014	Reliable Electricity Based on Electrochemical Systems (REBELS)	13	$37
2014	Cycling Hardware to Analyze and Ready Grid-Scale Electricity Storage (CHARGES)	2	$6.5
2014	Delivering Efficient Local Thermal Amenities (DELTA)	11	$32
2014	Methane Observation Networks with Innovative Technology to Obtain Reductions (MONITOR)	12	$39
2015	Accelerating Low-cost Plasma Heating and Assembly (ALPHA)	9	$31
2015	Advanced Research In Dry cooling (ARID)	15	$33

TABLE 1: ARPA-E PROGRAMS TO DATE			
FUNDING YEAR	**PROGRAM NAME**	**NUMBER OF PROJECTS**	**FUNDING AMOUNT ($ Million)[3]**
2015	GENerators for Small Electrical and Thermal Systems (GENSETS)	14	$37
2015	Transportation Energy Resources from Renewable Agriculture (TERRA)	6	$38
2015	Traveler Response Architecture using Novel Signaling for Network Efficiency in Transportation (TRANSNET)	5	$15
2015	Micro-scale Optimized Solar-cell Arrays with Integrated Concentration (MOSAIC)	11	$26
2015	OPEN 2015	39	$124
2015	Network Optimized Distributed Energy Systems (NODES)	12	$35
2016	Generating Realistic Information for the Development of Distribution and Transmission Algorithms (GRID DATA)	7	$11
2016	Single-Pane Highly Insulating Efficient Lucid Design (SHIELD)	14	$27
2016	Integration and Optimization of Novel Ion-Conducting Solids (IONICS)	16	$37
2016	Next-Generation Energy Technologies for Connected and Automated On-Road Vehicles (NEXTCAR)	11	$35
2016	Rhizosphere Observations Optimizing Terrestrial Sequestration (ROOTS)	10	$36
2016	Renewable Energy to Fuels Through Utilization of Energy-Dense Liquids (REFUEL)	16	$33
2017	Energy-Efficient Light-Wave Integrated Technology Enabling Networks that Enhance Datacenters (ENLITENED)	9	$25
2017	Power Nitride Doping Innovation Offers Devices Enabling SWITCHES (PNDIODES)	7	$6.9
2017	Creating Innovative and Reliable Circuits Using Inventive Topologies and Semiconductors (CIRCUITS)	21	$30
2017	Macroalgae Research Inspiring Novel Energy Resources (MARINER)	18	$22
2017	Saving Energy Nationwide in Structures with Occupancy Recognition (SENSOR)	15	$20
2017	Innovative Natural-gas Technologies for Efficiency Gain in Reliable and Affordable Thermochemical Electricity-generation (INTEGRATE)	8	$16
2018	Modeling-Enhanced Innovations Trailblazing Nuclear Energy Reinvigoration (MEITNER)	6	$14
2018	Duration Addition to electricity Storage (DAYS)	10	$28
2018	Building Reliable Electronics to Achieve Kilovolt Effective Ratings Safely (BREAKERS)	8	$21
2018	High Intensity Thermal Exchange through Materials and Manufacturing Processes (HITEMMP)	15	$29.2
2018	Grid Optimization (GO) Competition Challenge 1	10	$3.4

TABLE 1: ARPA-E PROGRAMS TO DATE			
FUNDING YEAR	**PROGRAM NAME**	**NUMBER OF PROJECTS**	**FUNDING AMOUNT ($ Million)[3]**
2018	OPEN 2018 (and related OPEN+ cohorts)	77	$202.8
2019	Aerodynamic Turbines Lighter and Afloat with Nautical Technologies and Integrated Servo-control (ATLANTIS)	13	$26
2019	Solicitation on Topics Informing New Program Areas (Topics A-F)	33	$38
2019	Design Intelligence Fostering Formidable Energy Reduction and Enabling Novel Totally Impactful Advanced Technology Enhancements (DIFFERENTIATE)	23	$15
2019	Solicitation on Topics Informing New Program Area (Topics G – H)	22	$21.3
2020	Environmental Security Technology Certification Program (ESTCP)	4	$3.2
2020	Performance-based Energy Resource Feedback, Optimization, and Risk Management (PERFORM)	12	$30.5
2019	Generating Electricity Managed by Intelligent Nuclear Assets (GEMINA)	9	$27
2019	Aviation-class Synergistically Cooled Electric-motors with iNtegrated Drives (ASCEND)	9	$14.5
2020	Breakthroughs Enabling Thermonuclear-fusion Energy (BETHE)	16	$35
2020	FLExible Carbon Capture and Storage (FLECCS)	12	$11.5
2020	Solicitation on Topics Informing New Project Areas (Topics I – K)	12	$10.4
2019	Range Extenders for Electric Aviation with Low Carbon and High Efficiency (REEACH)	9	$20
2020	Seeding Critical Advances for Leading Energy technologies with Untapped Potential (SCALEUP)	2	$24
2020	Systems for Monitoring and Analytics for Renewable Transportation Fuels from Agricultural Resources and Management (SMARTFARM)	6	$16.5
2020	Galvanizing Advances in Market-Aligned Fusion for an Overabundance of Watts (GAMOW)	6	$16.5
2020	Rapid Encapsulation of Pipelines Avoiding Intensive Replacement (REPAIR)	10	$33
2020	Solicitation on Topics Informing New Project Areas (Topics L – P)	19	$18.7

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FUNDING YEAR	**PROGRAM NAME**	**NUMBER OF PROJECTS**	**FUNDING AMOUNT ($ Million)[3]**
2020	Submarine Hydrokinetic and Riverine Kilo-megawatt Systems (SHARKS)	11	$35
2020	Ultrahigh Temperature Impervious Materials Advancing Turbine Efficiency (ULTIMATE)	17	$16
2020	Energy and Carbon Optimized Synthesis for the Bioeconomy (ECOSynBio)	15	$25
2021	Reducing Emissions of Methane Every Day of the Year (REMEDY)	12	$35
2021	OPEN 2021	68	$175
2021	Optimizing Nuclear Waste and Advanced Reactor Disposal Systems (ONWARDS)	11	$36
	TOTAL	**1,204**	**$2,821**