U.S. POLICY

ADVANCED RESEARCH PROJECTS AGENCY - ENERGY (ARPA-E): INNOVATION THROUGH THE U.S. DEPARTMENT OF ENERGY

CENTER FOR CLIMATE AND ENERGY SOLUTIONS

by

Sam Wurzelmann

April 2012

Creating a low-carbon future for the United States requires innovative clean energy technologies that are cost-effective compared to the fossil fuels the country has long relied on. The U.S. Department of Energy's Advanced Research Projects Agency – Energy (ARPA-E) was established in 2007 to help achieve this goal by supporting the research, development and demonstration of potential breakthrough technologies. ARPA-E received $858.8 million in federal funding through early 2012, and supported 180 technology projects with $521.7 million of awards. Projects ranged from enhancing wind turbine designs to creating underground energy storage and improving carbon capture and storage technologies. Beyond direct support, ARPA-E awards have helped companies leverage more than $200 million in additional private investment. This brief provides an overview of ARPA-E and highlights of supported projects.

THE ARPA-E PROGRAM

HISTORY

The Advanced Research Projects Agency – Energy (ARPA-E) was established under the America COMPETES Act of 2007 as a new agency within the U.S. Department of Energy (DOE) to fund innovative energy research. ARPA-E research projects span transformative technologies in energy storage, carbon capture, advanced biofuels, solar power, wind power, and other next generation energy technologies. The agency was reauthorized as part of the America COMPETES Reauthorization Act of 2010, through which its structure was slightly modified, and it was designated to receive increased funding authorizations for Fiscal Year (FY) 2011 through FY 2013.[1]

The idea for ARPA-E was generated by the 2007 National Academies report, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, which called for the creation of an agency to "support creative 'out-of-the-box' transformational generic energy research that industry by itself cannot or will not support, and in which risk may be high but success would provide dramatic benefits for the nation."[2] The agency's beginnings were inspired by the U.S. Department of Defense's Defense Advanced Research Project Agency (DARPA), which has transformed the technological landscape by catalyzing innovations in information technology (for example, the internet, which was originally ARPANET), advanced materials, global positioning systems (GPS), and microelectronics.[3] Similar to DARPA, ARPA-E was created to develop high-risk, high-payoff disruptive technologies.[4]

As defined by the America COMPETES Act of 2007, ARPA-E was created to meet the following goals:[5]

(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.

The report, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*, called for ARPA-E funding to increase from an initial $300 million per year to $1 billion per year 5 to 6 years later. Although legally created in 2007, it was not until 2009 that the agency received $403.8 million in initial funding, as part of the American Recovery and Reinvestment Act of 2009 (Pub.L. 111-5, Recovery Act) and Congressional appropriations. As of January 2012, ARPA-E has received $858.8 million in total federal funding and the agency has awarded $521.7 million to 180 projects. The agency weathered overall budget cuts in FY 2011 and FY 2012 and has bipartisan support, which increases the likelihood that Congress will continue to fund the program into the future.[6]

TABLE 1: ARPA-E ANNUAL FUNDING (DOLLARS IN MILLIONS)

Fiscal Year	Amount	Source
2009	$403.8[7]	Recovery Act Appropriation ($388.8 million) Other Congressional Appropriation ($15 million)
2010	0[8]	-
2011	180[9]	Congressional Appropriation
2012	275[10]	Congressional Appropriation
Total	**$858.8**	

WHY ARPA-E IS NEEDED

A low-carbon future for the United States will depend on the composition of its energy technology portfolio. Innovation is needed to develop clean energy technologies that are cost effective compared to the fuels currently dominating U.S. energy production and consumption: coal, oil, and natural gas.[11] Numerous challenges have blocked the pathway to achieving this goal, ranging from insufficient research and development (R&D) funding for clean energy technologies to competition with the subsidized fossil fuel-based energy infrastructure that the United States has historically relied upon. ARPA-E is helping the United States address these challenges.

One of the primary obstacles to energy innovation is insufficient private sector funding.[12] In other sectors, private sector R&D has been known to support innovation and foster "lead markets."[13] For example, the information technology and biopharmaceutical industries typically spend between 10 and 20 percent of their revenues on R&D. The biopharmaceutical industry spent an estimated $58.8 billion on R&D in 2007.[14] Clean energy technologies present significant economic opportunity for developing "lead markets" in the United States.[15] Despite this opportunity, U.S. private sector energy R&D investment was just 0.23 percent of revenues in 2007, while the industry average was 2.6 percent.[16] In 2010 the level of energy sector R&D spending had risen to just 0.3 percent of revenues.[17]

A variety of factors account for this lack of private investment in energy innovation.   It is difficult for companies to sustain support during the years it can take to move an energy technology from R&D to commercialization. Developers cannot capture R&D's full economic benefits of R&D because of "spillover" effects once a technology is commercialized.[18] In other cases, the high upfront costs of capital or the scale and scope of the R&D cannot be taken on alone by a single company or industry. In the United States, a lack of long-term, transparent clean energy policies also discourages greater private sector investment in low-carbon innovation. In a 2011 C2ES survey of business executives, the majority of respondents cited ambiguity in government policy support as the most important risk associated with low-carbon innovation.[19] A company is less willing to invest in an expensive low-carbon energy technology development project if there is uncertainty about how policies will affect the market demand for such technologies. ARPA-E helps to overcome these barriers with strategic public funding for breakthrough energy R&D. And while ARPA-E does not directly address policy uncertainty, it circumvents some of its effects by providing targeted funding and technical support to help businesses move up the learning curve and down the cost curve as they develop low-carbon innovations.

Venture capitalists have backed away somewhat from funding energy technology startups, likely due to their capital-intensive nature and the collapse of U.S. clean energy policy in 2009, making it increasingly difficult to commercialize a new technology concept.[20] Early-stage venture capital, the riskiest stage of venture capital funding, for renewable energy technologies grew 41 percent between 2009 and 2010 to $930 million, but the 2010 figure was still 38 percent lower than its pre-recession peak in 2008.[21] ARPA-E funds projects deemed too risky by the private sector and thus helps bridge this investment gap.

Dwindling government support has also contributed to the historical underinvestment in disruptive energy technologies. DOE's funding for energy technology R&D has decreased over time, falling 85 percent from $5.5 billion in FY 1978 to $793 million in FY 2005, when adjusted for inflation. This lack of government support has made it difficult for U.S. energy technology efforts to achieve more than incremental advances , contributing to the United States' continued dependence on fossil fuels.[22] DOE R&D funding rebounded in FY 2009 and FY 2010, to $13.2 billion and $10.6 billion as part of the economic stimulus package. Yet this level of financial support is still far below federal R&D spending in other sectors. In those same years, the government spent $81.1 and $81.0 billion for Department of Defense R&D, and $41.5 billion and $31.1 billion on Department of Health and Human Services R&D.[23] Compared to historical government investments in energy R&D, ARPA-E is funding more innovative technologies with the potential to significantly reduce the nation's dependence on fossil fuels.

Another major obstacle to energy innovation is the inertia of the existing fossil fuel-based energy generation and consumption infrastructure. Oil, coal, and natural gas have historically been the United States' principal energy sources[24] and receive more direct and indirect subsidies than renewable energy sources. The Environmental Law Institute reported that between 2002 and 2008, cumulative fossil fuel subsidies, including R&D funding, totaled $72.5 billion compared to $29 billion for renewable power technologies. The largest subsidies for fossil fuels were written into the U.S. Tax Code as permanent provisions, while many subsidies for renewable power technologies are newer provisions of law that must be renewed regularly, with expiration dates that limit their certainty.[25] This situation provides relatively more certainty for fossil fuel-based businesses when making investment decisions. Without economy-wide policies that overcome energy market barriers and cease to favor fossil fuels, there is less incentive to invest in innovative energy R&D. ARPA-E is working to break through this stagnancy by funding early-stage breakthrough research. Furthermore, as explained later in this paper, ARPA-E has cultivated partnerships to provide commercial-scale test beds and potential customers for technology projects in need of greater resources and scale to test market-readiness.

TABLE 2: ARPA-E PROGRAMS AND DESCRIPTIONS	
Program Name	**Description**
Plants Engineered to Replace Oil (PETRO)	PETRO aims to optimize the biochemical processes of energy capture and conversion, enabling crops that deliver more energy per acre with less processing.
Rare Earth Alternatives in Critical Technologies (REACT)	REACT targets early-stage technology alternatives that reduce or eliminate dependence on rare earth materials by developing substitute materials for electric vehicle motors and wind generators.
High Energy Advanced Thermal Storage (HEATS)	HEATS supports the development of revolutionary cost-effective thermal energy storage technologies that could dramatically improve performance for a variety of critical energy applications.
Green Electricity Network Integration (GENI)	GENI develops innovative control software and high-voltage hardware that can reliably control the electric grid, specifically for cost-optimizing intermittent energy sources and controlling power flow in real-time.
Solar Agile Delivery of Electrical Power Technology (Solar ADEPT)	Solar ADEPT focuses on integrating advanced power electronics into solar panels and solar farms to extract and deliver energy more efficiently.
Batteries for Electrical Energy Storage in Transportation (BEEST)	BEEST supports advanced batteries that will enable broader public adoption of electric vehicles and shift transportation energy reliance from oil to the domestically powered U.S. electric grid.
Innovative Materials & Processes for Advanced Carbon Capture Technologies (IMPACCT)	IMPACCT aims to revolutionize technologies that prevent carbon dioxide produced by coal-fired power plants from entering the atmosphere and contributing to climate change.
Grid-scale Rampable Intermittent Dispatchable Storage (GRIDS)	GRIDS supports new technologies that enable widespread use of cost-effective grid-scale energy storage and balance the short-duration variability in renewable generation.
Agile Delivery of Electrical Power Technology (ADEPT)	ADEPT seeks materials for key advances in soft magnetics, high-voltage switches, and reliable, high-density charge storage that will reduce energy costs and consumption.
Electrofuels	Electrofuels explores the use of microorganisms to harness energy and convert carbon dioxide into liquid fuels. According to ARPA-E, its projects could be ten times more efficient than current approaches.
Building Energy Efficiency Through Innovative Thermodevices (BEETIT)	BEETIT seeks to develop energy-efficient building cooling technologies that will reduce energy consumption and greenhouse gas emissions.

HOW IT WORKS

ARPA-E has spelled out a rigorous process for evaluating and advancing energy technology innovations. ARPA-E is comprised of several programs, which fund projects addressing specific energy needs. The process of developing an ARPA-E program begins by exploring particular energy needs through technical workshops convening science, technology, and business experts on current and emerging energy technology solutions. The workshops focus on bridging the gap between basic and applied R&D,[26] and connecting science to technology and markets.

Following the workshops, ARPA-E can propose the creation of a new program if it meets structural requirements for program formation. After a period of internal feedback, a new ARPA-E program is then created and a funding opportunity announcement (FOA) is publicly released to solicit project proposals.[27]

As of January 2012, 11 ARPA-E programs have been created (see Table 2).[28]

Applicants for program funding and support may include for-profit entities, educational institutions, incorporated non-profits, and a variety of U.S. government entities. ARPA-E considers external feedback from leading energy experts when deciding which projects to fund. Applicants are allowed to provide rebuttals and answer clarification questions before the agency makes final funding decisions.[29]

ARPA-E funds projects with the following characteristics:[30]

- **High Impact:** ARPA-E funded projects enhance the economic and energy security of the United States; ensure U.S. technological leadership in developing and deploying advanced energy technologies; and provide major economic impact and social improvements for Americans.
- **Technological Breakthroughs:** ARPA-E identifies disruptive energy technologies that can make current technologies obsolete.
- **Value-Added:** ARPA-E program areas and selected projects advance the R&D of early-stage transformational technologies that is not being advanced by others.
- **Best-in-Class Teams:** ARPA-E nurtures project development by coupling scientists and engineers in teams to rapidly advance technological innovation in energy, bringing together talented people from diverse areas of science, technology, and business that otherwise might not work together.

On the Technology Readiness Level scale—a frequently used measure of a technology's stages of development—the majority of ARPA-E funded projects fall between levels two and four, a space ARPA-E considers the "valley of death" for technology development, which many public and private investors consider too risky (see Table 3).[31]

TABLE 3: TECHNOLOGY READINESS LEVELS

Technology Readiness Level (TRL)	Description
TRL 1	Basic principles observed and reported
TRL 2	Technology concept and/or application formulated
TRL 3	Analytical and experimental critical function and/or proof of concept
TRL 4	Component and/or breadboard validation in laboratory environment
TRL 5	Component and/or breadboard validation in relevant experiment
TRL 6	System/Subsystem model or prototype demonstration in relevant environment
TRL 7	System prototype demonstration in an operational environment
TRL 8	Actual system completed and qualified in an operation environment
TRL 9	Actual system proven through successful mission operations

The TRL descriptions are defined by ARPA-E.[32]

Once selected, projects are required to prepare a "Technology-to-Market" plan to ensure technologies are ready for the market.[33] This step is required in order to increase the likelihood that a technology has a widespread impact. ARPA-E brings together advisors and stakeholders to provide feedback and support for these plans. This includes working with ARPA-E Technology-to-Market advisors and outside engagement with corporations, investors, service providers, and government and regulatory bodies.[34]

ARPA-E FUNDING AND IMPACT

FUNDING RESULTS

As of December 2011, ARPA-E invested $521.7 million in 180 projects.[35] Table 4 details the project funding announcements and Table 5 highlights the federal funding totals for the different ARPA-E programs. Figure 1 breaks down the projects by lead organization type.

Figure 1: ARPA-E Projects by Organization Type

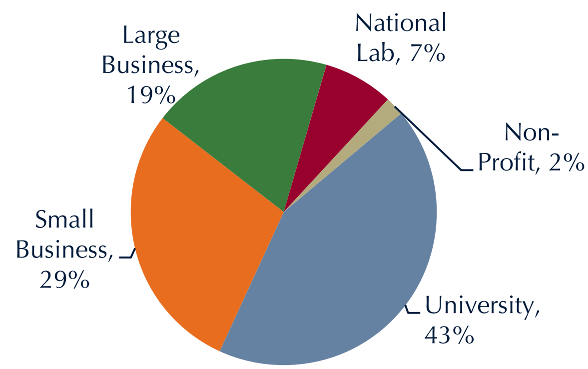

TABLE 4: PROJECT FUNDING ANNOUNCEMENTS (DOLLARS IN MILLIONS)

Date	Total Projects	Amount
October 26, 2009[40]	36	$149.2
April 29, 2010[41]	37	106.4
July 12, 2010[42]	42	91.9
September 10, 2010[43]	6	9.6
September 29, 2011[44]	61	159.1
Total	**182**	**$516**[45]

PROGRAM HIGHLIGHTS

A number of ARPA-E projects have already gained commercial traction beyond the ARPA-E stage of investment. To date, ARPA-E projects cumulatively have received at least $200 million in private investment beyond ARPA-E funding, and have filed 17 patents.[36] Below are highlights of particular projects, organized by ARPA-E program and with the funding amount and date awarded.[37]

Open Funding Opportunity Announcement

1366 Technologies, Lexington, MA | $4,000,000 | October 26, 2009

1366 Technologies produced one of ARPA-E's earliest breakthroughs. The company developed a solar wafer manufacturing process that could reduce the cost of silicon wafers by 80 percent, potentially reducing the cost of solar photovoltaic power by half. With success, it could increase U.S. solar wafer exports, capturing a large portion of the $10 billion per year global market.[38] Based on its success, 1366 Technologies has secured more than $194.4 million in additional public and private investments.[39]

TABLE 5: PROGRAM PROJECTS AND FUNDING		
Program Name	**Total Projects**	**Total Funding Awarded. Dollars in Millions.**
Plants Engineered to Replace Oil (PETRO)[46]	10	$36.0
Rare Earth Alternatives in Critical Technologies (REACT)[47]	14	31.6
High Energy Advanced Thermal Storage (HEATS)[48]	15	37.3
Green Electricity Network Integration (GENI)[49]	15	39.4
Solar Agile Delivery of Electrical Power Technology (Solar ADEPT)[50]	7	14.7
Batteries for Electrical Energy Storage in Transportation (BEEST)[51]	10	34.6
Innovative Materials & Processes for Advanced Carbon Capture Technologies (IMPACCT)[52,53]	15	31.4
Grid-scale Rampable Intermittent Dispatchable Storage (GRIDS)[54,55]	12	27.6
Agile Delivery of Electrical Power Technology (ADEPT)[56]	14	34.6
Electrofuels[57]	13	41.2
Building Energy Efficiency Through Innovative Thermodevices (BEETIT)[58,59]	16	29.7
Other Projects[60,61]	41	158.0
Total	**182**	**$516**[62]

FloDesign Wind Turbine Corp., Wilbraham, MA | $8,325,400 | October 26, 2009

FloDesign is developing a highly efficient wind turbine inspired by the design of a jet engine. The company's Mixer Ejector Wind Turbine can deliver at least three times the power extraction efficiency of a traditional wind turbine with the same size rotor, or the same power with 50 percent of the rotor size. It is less expensive to produce and operate than existing wind turbines, increasing its potential for widespread deployment.[63] FloDesign has raised at least $65 million in additional public and private investment.[64]

Batteries for Electrical Energy Storage in Transportation (BEEST)

24M Technologies/Massachusetts Institute of Technology, Cambridge, MA | $5,975,331 | April 29, 2010

24M and its MIT-based scientists are developing a new lithium-ion battery for vehicles using a semi-solid, high energy density, rechargeable storage material. Early tests suggest battery costs of less than $100 per kilowatt hour can be obtained.[65] For comparison, the cost of lithium-ion batteries used in today's electric vehicles is estimated at $750 to $800 per kilowatt hour.[66] 24M has raised over $15.9 million in financing from public and venture capital investments.[67]

Stanford University, Stanford, CA | $1,501,742 | April 29, 2010

Stanford University researchers are developing and commercializing an "All-Electron Battery." The advanced battery would move electrons rather than ions and utilize a novel design that may provide higher energy and power density, and a longer lifetime than typical battery designs.[68] The research project has raised $26.5 million in public and private funding.[69]

Innovative Materials & Processes for Advanced Carbon Capture Technologies (IMPACCT)

Codexis, Inc., Redwood City, CA | $4,657,045 | April 29, 2010

Codexis is developing a low-cost carbonic anhydrase catalyst for more efficient carbon dioxide capture processes at power plants compared to current methods. In December 2010, Codexis announced a partnership with Alstom SA, the world's third-largest power-equipment manufacturer, to develop and test customized catalysts for use in power plants.[70]

University of Kentucky – Center for Applied Energy Research, Lexington, KY | $2,011,578 | April 29, 2010

Researchers at the University of Kentucky are developing a hybrid absorption solvent/catalytic membrane that can be retrofit onto existing coal-fired power plants. This catalytic membrane has great potential to reduce the costs associated with separating carbon dioxide from flue gas, while being conveniently integrated with traditional carbon capture processes.[71]

Grid-Scale Rampable Intermittent Dispatchable Storage (GRIDS)

General Compression, Newton, MA | $750,000 | July 12, 2010

General Compression is developing a compressed air energy storage process that will help to ameliorate the challenge of intermittency from wind energy and other renewable power sources. The process stores intermittent electricity as energy in the form of high-pressure air in underground geologic formations. The design allows electricity to be generated on demand when air is released from storage. This storage has potential to accelerate the integration of renewable electricity sources into the grid. General Compression has raised $85.7 million from public and private investors, including Duke Energy, US Renewables Group, and ConocoPhillips.[72]

Primus Power Corporation, Alameda, CA | $2,000,000 | July 12, 2010

Primus Power has developed low-cost, metallic flow battery[73] electrodes that take advantage of existing high volume industrial processes for manufacturing. By utilizing existing industrial processes, cost reductions are achieved that decrease prices for energy storage, thereby helping to address renewable energy intermittency. The company has raised $13 million in public and private investments.[74]

Agile Delivery of Electrical Power Technology (ADEPT)

Transphorm, Inc., Goleta, CA | $2,950,000 | July 12, 2010

Transphorm is working to reduce electric power conversion inefficiencies through its semiconductor devices for a variety of electrical systems and devices, including motor drives, power supplies, and inverters for solar panels and electric vehicles.[75] Gallium nitride can reduce losses in electrical power conversion by 10.5 percent of total U.S. electricity generation. These losses equate to 13 times the generation of all wind and solar power, or the output of 318 coal power plants, and result in $40 billion in losses in the United States.[76] Such higher efficiency motors could save this country. $13 billion per year, with enough electricity savings to power 13 million homes. Transphorm has raised $68.5 million in total investment.[77]

Cree, Durham, NC | $5,200,003 | July 12, 2010

Scientists at Cree are developing advanced silicon carbide power transistors with potentially major energy efficiency advantages over existing technologies for power substations and grid power applications. They have the potential to reduce power conversion electricity losses by 50 percent compared to existing technologies, in addition to reducing 8,000 pound transformers to an eightieth of the original weight.[78]

Electrofuels

OPX Biotechnologies, Boulder, CO | $5,997,490 | April 29, 2010

OPX Biotechnologies is developing bacteria that use hydrogen and carbon dioxide to produce a low cost liquid biodiesel, with water as its only byproduct. If successful, the project would result in a biofuel creation process that does not require large swaths of land that biofuels typically need. The company has raised at least $36.5 million from private investors after being awarded the ARPA-E funding.[79]

Columbia University, New York, NY | $543,394 | April 29, 2010

Columbia University researchers are utilizing a bacteria, Nitrosomonas europaea, to convert carbon dioxide and ammonia, an abundant and affordable chemical, into a liquid transportation fuel. The technology being developed will produce isobutanol, an alcohol and drop-in fuel that performs more similarly to gasoline than ethanol.[80] The technology will not require significant acreage and is expected to be more efficient than current photosynthetic-dependent biofuel production systems. In fact, the researchers' data have suggested that the bacteria can convert ammonia to energy at very high efficiencies.[81]

Building Energy Efficiency Through Innovative Thermodevices (BEETIT)

University of Notre Dame, Notre Dame, Indiana | $2,817,926 | July 12, 2010

University of Notre Dame researchers are developing an advanced carbon dioxide-based heating and cooling process that could replace current building heating, ventilating, and air conditioning systems. If successful, their processes have the potential to significantly reduce the use of hydrofluorocarbon refrigerants, which have more than 1,000 times the global warming potential of carbon dioxide.

Sheetak, Inc., Austin, TX | $1,223,400 | July 12, 2010

Sheetak is developing a refrigeration system that produces cold air using less energy and without using fluids with global warming potential. Its design is planned to lower cost and increase the reliability of refrigeration systems, which has the potential to accelerate emissions reductions.

KEY PARTNERSHIPS

As tasked by the America COMPETES Act of 2007 and its 2010 amendments, over time ARPA-E has formed governmental and non-governmental partnerships to strengthen its work and provide outlets for project demonstration and deployment.[82]

Furthering a 2010 U.S. DOE and U.S. Department of Defense (DOD) memorandum of understanding aimed at improving U.S. national security, in March 2011 ARPA-E announced a partnership with the U.S. Navy. Through this joint initiative, the DOD and ARPA-E requested $25 million each for FY 2012 to support advanced energy research.[83] One of the initiative's primary projects is to develop small, scalable, Hybrid Energy Storage Modules (HESMs) that combine energy generation and storage in a modular unit, aiming to extend energy endurance and energy density by up to 30 percent compared to existing technologies. The second project will leverage ARPA-E's GRIDS program to evaluate how to utilize large scale energy storage to improve energy reliability and energy security on more than 500 DOD installations.[84] Beyond reducing energy use by the DOD, which is the nation's single largest consumer of energy,[85] successful technology advancements may have crossover potential for commercial civilian markets. Both initiatives could enable electrical grids to maintain reliability while matching industrial and residential energy consumption to intermittent renewable power generation that cannot currently be dispatched.[86]

In addition to its partnership with the DOD, ARPA-E has secured grid-scale test beds for technologies. Aiming to provide opportunities for testing and deploying ARPA-E projects in commercial markets, in April 2011 ARPA-E signed a memorandum of understanding with Duke Energy and the Electric Power Research Institute (EPRI).[87] Both Duke Energy and EPRI will offer testing facilities for ARPA-E technology projects, while Duke could also test deployment of various technologies directly on the grid.[88] Duke Energy is one of the largest energy companies in the United States, serving approximately 4 million customers with 36,000 megawatts of electric generation capacity.[89] EPRI is a non-profit research organization focusing on the electricity industry.[90]

Both of these partnerships should strengthen ARPA-E projects' success, by providing large-scale testing of technologies and building relationships with potential customers.

CONCLUSION

Since ARPA-E's creation, its funding has been lower and more uncertain than was originally proposed.[91] The National Academies report, *Rising Above the Gathering Storm,* called for ARPA-E funding to increase from an initial $300 million per year to $1 billion per year 5 to 6 years later.[92] ARPA-E has received a cumulative sum of just $858.8 million for energy innovation and funding levels are not expected to reach the recommended $1 billion by 2013. Nevertheless, the agency weathered overall federal budget cuts as funding increased from FY 2011 to FY 2012.[93] Despite the financial pressure from budgetary battles, ARPA-E does have bipartisan support, which increases the likelihood that Congress will continue to fund the program into the future.[94] In the White House's FY 2013 budget, President Obama called for increasing the agency's funding to $350 million.[95]

The U.S. Congress has the opportunity to enable the development of breakthrough energy technologies by demonstrating a strong commitment to ARPA-E. Although there has historically been insufficient private sector funding for transformative energy R&D, ARPA-E has helped companies to leverage public capital to encourage private investment. The U.S. government has a long history of supporting the development of today's most innovative and advanced technologies. With 180 projects already underway, vast potential exists for ARPA-E to have a wide-ranging impact in developing game-changing technologies that will reduce the nation's dependence on fossil fuels.

ENDNOTES

1 America COMPETES Reauthorization Act of 2010, Pub. L. No. 111-358 (2011), http://www.gpo.gov/fdsys/pkg/PLAW-111publ358/pdf/PLAW-111publ358.pdf.

2 Committee on Prospering in the Global Economy of the 21st Century: An Agenda for American Science and Technology, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future* (Washington, DC: The National Academies Press, 2007), p8.

3 Dr. Richard Van Atta, "Fifty Years of Innovation and Discovery" in *DARPA: 50 Years of Bridging the Gap* (Washington, DC: Faircount LLC, 2008). DARPA was established in 1958, with an initial budget of $500 million, in response to the Soviet Sputnik satellite. Committee on Prospering in the Global Economy, *Rising Above the Gathering Storm*; DARPA's fiscal year 2012 budget reaches nearly $3.1 billion per year. U.S. Department of Defense, *Department of Defense Fiscal Year (FY) 2012 Budget Estimates: Defense Advanced Research Projects Agency* (Washington, DC: U.S. Department of Defense, 2011), http://www.darpa.mil/WorkArea/DownloadAsset.aspx?id=2400.

4 "Mission," *ARPA-E*, accessed December 28, 2011, http://arpa-e.energy.gov/About/Mission.aspx.

5 America COMPETES Act, Pub. L. 110-69, 121 Stat. 572 (2007), http://arpa-e.energy.gov/LinkClick.aspx?fileticket=w9GGYB4DJlE%3d&tabid=165.

6 "At MIT, Energy Secretary Chu says he hopes ARPA-E will survive budget cuts," *Boston.com*, November 30, 2011, http://www.boston.com/business/technology/innoeco/2011/11/at_mit_energy_secretary_chu_sa.html.

7 FY 2011 Congressional Budget, *Energy Transformation Acceleration Fund: Advanced Research Projects Agency – Energy (ARPA-E) Proposed Appropriation Language*, http://arpa-e.energy.gov/LinkClick.aspx?fileticket=FzuPHgdX6r8%3d&tabid=184.

8 The United States House of Representatives Report H. Rpt. 111-203 provides explanation for why the FY 2010 appropriations bill (Public Law 111-85) did not fund ARPA-E. It stated that the FY 2009 congressional appropriations and the Recovery Act funding would allow ARPA-E fund its first round of awards in FY 2010, and noted, "The decision not to provide any additional funding for ARPA-E in fiscal year 2010 beyond funding already provided does not in any way suggest a lack of commitment to this new program by Committee." John F. Sargent Jr., *America COMPETES Act and the FY2010 Budget* (Washington, DC: Congressional Research Service, 2010), http://www.fas.org/sgp/crs/misc/R40519.pdf.

9 "ARPA-E Overview," *ARPA-E*, accessed December 12, 2011, http://arpa-e.energy.gov/About/FAQs/ARPAEOverview.aspx.

10 Consolidated Appropriations Act, 2012, H.R. 2055, 112th Congress (2011), http://democrats.rules.house.gov/112/text/cof_b.pdf.

11 U.S. Energy Information Administration, *U.S. Annual Energy Review* (Washington, DC: U.S. Energy Information Administration, 2011), http://www.eia.gov/totalenergy/data/annual/pdf/sec2_3.pdf.

12 The market deficiencies in energy are classic externalities, environmental and other societal damages caused by fossil fuels that are not included in the fuel price.

13 "Lead markets" are high-growth potential markets for research and innovation-rich goods and services. "Lead markets – gateway to growth?" *EurActiv.com*, December 16, 2007, http://www.euractiv.com/innovation/lead-markets-gateway-growth/article-167684. For more on lead markets, see Marian Beise and Klaus Rennings, *Lead Markets of Environmental Innovations: A Framework for Innovation and Environmental Economics* (Center for European Economic Research), ftp://ftp.zew.de/pub/zew-docs/dp/dp0301.pdf.

14 William B. Bonvillian and Charles Weiss, *Structuring an Energy Technology Revolution* (Massachusetts: MIT Press, 2009).

15 Pew Center on Global Climate Change, *In Brief: Clean Energy Markets: Jobs and Opportunities* (Arlington, Virginia: Pew

Center on Global Climate Change 2011), http://www.c2es.org/docUploads/clean-energy-markets-update2011_0.pdf.

16 Bonvillian and Weiss. *Structuring an Energy Technology Revolution.*

17 Battelle, "2011 Global R&D Funding Forecast" *R&D Mag*, December 2010, http://www.battelle.org/aboutus/rd/2011.pdf

18 Spillover effects are externalities of economic activity that affect those not directly involved in that activity, thus preventing a business from capturing its full return on investment. In the case of environmental friendly technologies, they are documented to reduce a private company's incentive to innovate. Carolyne Fischer, *Emissions Pricing, Spillovers, and Public Investment in Environmentally Friendly Technologies* (Washington, DC: Resources for the Future, 2004), http://www.rff.org/documents/RFF-DP-04-02.pdf.

19 Thirty-five companies, ranging in size from $600 million to $285 billion in annual revenues and with a median annual R&D expenditure of $575 million, completed the survey. The Center for Climate and Energy Solutions, *A Survey of Company Perspectives on Low-Carbon Business Innovation* (Arlington, VA: The Center for Climate and Energy Solutions, 2011), http://www.c2es.org/docUploads/survey-results-paper.pdf.

20 Alan Marks, interview by Monica Trauzzi, December 16, 2010, *OnPoint with Monica Trauzzi*, http://www.eenews.net/tv/2011/12/16/; Christopher Martin, "Green Startups: Trapped in the 'Valley of Death'," *Bloomberg Businessweek*, October 7, 2010, http://www.businessweek.com/technology/content/oct2010/tc2010106_187335.htm.

21 United Nations Environment Programme and Bloomberg New Energy Finance, *Global Trends in Renewable Energy Investment 2011* (United Nations Environment Programme, 2011).

22 U.S. Government Accountability Office, *Advanced Energy Technologies: Key Challenges to their Development and Deployment* (Washington, DC: U.S. Government Accountability Office, 2007), http://www.gao.gov/assets/120/115602.pdf.

23 The higher figures for 2009 are primarily the result of funding from the American Recovery and Reinvestment Act of 2009. John F. Sargent Jr., *Federal Research and Development Funding: FY2012* (Washington, DC: Congressional Research Service, 2011), http://www.fas.org/sgp/crs/misc/R41098.pdf.

24 U.S. Energy Information Administration, "5. U.S. Primary Energy Consumption Estimates by Source, 1775-2010," in *Energy Perspectives 2011* (Washington, DC: U.S. Energy Information Administration, 20110), http://www.eia.gov/totalenergy/data/annual/pdf/perspectives_2010.pdf.

25 The report defines fossil fuels as "petroleum and its byproducts, natural gas, and coal products," while renewable fuels are defined as, "wind, solar, biofuels and biomass, hydropower, and geothermal energy production." Environmental Law Institute, *Estimating U.S. Government Subsidies to Energy Sources: 2002-2008* (Washington, DC: Environmental Law Institute, September 2009), http://www.elistore.org/Data/products/d19_07.pdf.

26 Basic research, as defined by Lawrence Berkeley National Lab, is driven by a scientist's curiosity and the main motivation is to expand man's knowledge. There is no obvious commercial value to the discoveries of basic research. Applied research is designed to solve practical problems of the modern world. "What is Basic Research?" Lawrence Berkeley National Lab, accessed December 28, 2011, http://www.lbl.gov/Education/ELSI/Frames/research-basic-defined-f.html; "What is Applied Research?" Lawrence Berkeley National Lab, accessed December 28, 2011, http://www.lbl.gov/Education/ELSI/Frames/research-applied-defined-f.html.

27 ARPA-E, *FY2010 Annual Report.* (Washington, DC: ARPA-E, 2011), http://arpa-e.energy.gov/LinkClick.aspx?fileticket=JPgM-ETf-o0%3d&tabid=438.

28 "Programs," *ARPA-E*, accessed December 12, 2011, http://arpa-e.energy.gov/ProgramsProjects/Programs.aspx. The first FOA was issued before programs were created, so funding was not centered on a specific technological goal as in subsequent FOAs.

29 ARPA-E, *FY2010 Annual Report*; "Funding Opportunities," *ARPA-E*, accessed December 19, 2011, http://arpa-

e.energy.gov/About/FAQs/FundingOpportunities.aspx#Eligibility.

30 ARPA-E, *FY2010 Annual Report.*

31 ARPA-E, *FY2010 Annual Report.*

32 ARPA-E, *FY2010 Annual Report.*

33 "Technology-to-Market Overview," *ARPA-E*, December 12, 2011, http://arpa-e.energy.gov/FundingAgreements/TechnologytoMarket/HowtheProgramWorks.aspx. "ARPA-E Technology-to-Market Planning," *ARPA-E*, accessed December 12, 2011, http://arpa-e.energy.gov/FundingAgreements/TechnologytoMarket/Planning.aspx.

34 ARPA-E, *FY2010 Annual Report.*

35 "Department of Energy Awards $156 Million for Groundbreaking Energy Research Projects," *ARPA-E*, September 29, 2011, http://arpa-e.energy.gov/media/news/tabid/83/vw/1/itemid/39/department-of-energy-awards-%24156-million-for-groundbreaking-energy-research-projects.aspx.

36 "ARPA-E Issues Open Call for Transformational Energy Technologies,"*ARPA-E*, accessed March 31, 2012, http://arpa-e.energy.gov/media/news/tabid/83/vw/1/itemid/49/Default.aspx. Matt Hourihan and Matthew Stepp, *ARPA-E Merits Full Funding* (Washington, DC: The Information Technology and Innovation Foundation, 2011), http://www.itif.org/files/2011-arpa-e-funding.pdf.

37 These projects are in no way endorsed by the Center for Climate and Energy Solutions, but are merely highlighted to provide a window into the realms of energy research ARPA-E is funding. Projects in the remaining five programs (PETRO, REACT, HEATS, GENI, and Solar ADEPT) were selected at the end of September, 2011 and thus, project progress updates are limited.

38 ARPA-E, *FY2010 Annual Report.*

39 "Solar Program Highlights," *SunShot Initiative*, accessed December 19, 2011, http://www1.eere.energy.gov/solar/sunshot/funding.html; Matthew Wald, "2 More Solar Companies Get U.S. Loan Backing," *New York Times*, September 7, 2011, http://www.nytimes.com/2011/09/08/business/energy-environment/2-more-solar-companies-get-us-loan-backing.html?_r=2; "1366 Technologies Raises $20 Million Series B Financing Round," *1366 Technologies*, accessed December 19, 2011, http://www.1366tech.com/1366-technologies-raises-20-million-series-b-financing-round/;

40 The first open funding opportunity announcement notes that 37 projects worth $151 million were awarded grants. The Pennsylvania State University direct solar fuels project was canceled. "Transformational Energy Research Projects Win $151 Million in Funding," *ARPA-E*, October 26, 2009, http://arpa-e.energy.gov/media/news/tabid/83/vw/1/itemid/13/transformational-energy-research-projects-win-%24151-million-in-funding.aspx.

41 "Vice President Biden Announces Recovery Act Funding for 37 Transformational Energy Research Projects," *ARPA-E*, April 29, 2010, http://arpa-e.energy.gov/media/news/tabid/83/vw/1/itemid/21/vice-president-biden-announces-recovery-act-funding-for-37-transformational-energy-research-projects.aspx.

42 The July 12, 2010 project award announcement notes that 43 projects worth $92 were awarded grants. The Counseling & Consulting Associates project from this announcement was canceled. "Department of Energy Awards $92 Million for Groundbreaking Energy Research Projects," *ARPA-E*, July 12, 2010, http://arpa-e.energy.gov/media/news/tabid/83/vw/1/itemid/22/department-of-energy-awards-%2492-million-for-groundbreaking-energy-research-projects.aspx.

43 "Secretary Chu Awards $9.6 Million for Transformational Energy Research Projects," *ARPA-E*, September 10, 2010, http://arpa-e.energy.gov/media/news/tabid/83/vw/1/itemid/23/secretary-chu-awards-%2496-million-for-transformational-

energy-research-projects.aspx.

44 The 'FOA 4 Technical Descriptions' document highlights 61 projects worth $159.1 million. "FOA 4 Technical Descriptions," *ARPA-E*, last updated November 16, 2011, http://arpa-e.energy.gov/LinkClick.aspx?fileticket=QHWJySjQEbk%3d&tabid=83. "Department of Energy Awards $156 Million for Groundbreaking Energy Research Projects," *ARPA-E*.

45 These numbers are slightly different than those provided in ARPA-E's press releases. This is most likely due to a few projects being canceled or having the terms of the award changed. Data was calculated based on project and technical descriptions, and data available on the website. The endnotes in this table denote a few of the changed projects.

46 "Plants Engineered to Replace Oil (PETRO)," *ARPA-E*, accessed December 12, 2011, http://arpa-e.energy.gov/ProgramsProjects/PETRO.aspx.

47 "Rare Earth Alternatives in Critical Technologies (REACT)," *ARPA-E*, accessed December 12, 2011, http://arpa-e.energy.gov/ProgramsProjects/REACT.aspx.

48 "High Energy Advanced Thermal Storage (HEATS),"*ARPA-E*, accessed December 12, 2011, http://arpa-e.energy.gov/ProgramsProjects/HEATS.aspx.

49 "Green Electricity Network Integration (GENI)," *ARPA-E*, accessed December 12, 2011, http://arpa-e.energy.gov/ProgramsProjects/GENI.aspx.

50 "Solar Agile Delivery of Electrical Power Technology (Solar ADEPT),"*ARPA-E*, accessed December 12, 2011, http://arpa-e.energy.gov/ProgramsProjects/SolarADEPT.aspx.

51 "ARPA-E Project Selections, April 29, 2010" *ARPA-E*, accessed December 12, 2011, http://arpa-e.energy.gov/LinkClick.aspx?fileticket=mK6vhQztzb4%3d&tabid=83.

52 "Innovative Materials & Processes for Advanced Carbon Capture Technologies (IMPACCT)," *ARPA-E*, accessed December 12, 2011, http://arpa-e.energy.gov/ProgramsProjects/IMPACCT.aspx.

53 "ARPA-E Project Selections, April 29, 2010," *ARPA-E*.

54 "Grid Scale Rampable Intermittent Dispatchable Storage (GRIDS)," *ARPA-E*, accessed December 12, 2011, http://arpa-e.energy.gov/ProgramsProjects/GRIDS.aspx.

55 "ARPA-E Project Selections, July 10, 2010," *ARPA-E*, accessed December 12, 2011, http://arpa-e.energy.gov/LinkClick.aspx?fileticket=EuZA5Wf5GHI%3d&tabid=83.

56 "ARPA-E Project Selections, July 10, 2010," *ARPA-E*.

57 "ARPA-E Project Selections, April 29, 2010," *ARPA-E*.

58 "Building Energy Efficiency Through Innovative Thermodevices (BEETIT)," *ARPA-E*, accessed December 12, 2011, http://arpa-e.energy.gov/ProgramsProjects/BEETIT.aspx.

59 "ARPA-E Project Selections, July 10, 2010," *ARPA-E*.

60 Other projects focus areas include: biomass energy, building efficiency, carbon capture, conventional energy, direct solar fuels, energy storage, renewable power, vehicle technologies, waste heat capture, and water. "Other Projects," *ARPA-E*, accessed January 27, 2012, http://arpa-e.energy.gov/ProgramsProjects/OtherProjects.aspx; ARPA-E, *FY2010 Annual Report*.

61 The project 'Cryogenic Carbon Capture', funded within these 6 projects, is an IMPACCT project. "Secretary Chu Awards $9.6 Million for Transformational Energy Research Projects," *ARPA-E*.

62 These numbers are slightly different than those provided in ARPA-E's press releases. This is most likely due to a few projects being canceled or having the terms of the award changed. Data was calculated based on project and technical descriptions, and data available on the website. The endnotes in this table denote a few of the changed projects.

63 “ARPA-E’s 37 Projects Selected from Funding Opportunity Announcement #1,” *ARPA-E*, accessed December 12, 2011, http://arpa-e.energy.gov/LinkClick.aspx?fileticket=aBlsCuR97m4%3d&tabid=221. Photo available at “FloDesign Wind Turbine Corp. of Wilbraham awarded $8.3 million to help develop new turbine,” *Masslive.com* , October 26, 2009, http://www.masslive.com/news/index.ssf/2009/10/flodesign_wind_turbine_corp_of.html.

64 Robert Gavin, “More than the money,” *Boston.com*, May 16, 2010, http://www.boston.com/news/science/articles/2010/05/16/more_than_the_money/.

65 ARPA-E, *FY2010 Annual Report*.

66 Jim Witkin, “Building Better Batteries for Electric Cars,” *New York Times*, March 30, 2011, http://www.nytimes.com/2011/03/31/business/energy-environment/31BATTERIES.html

67 ARPA-E, *FY2010 Annual Report*.

68 “Army High Performance Computing Research Center,” *Stanford University Mechanical Engineering*, accessed January 3, 2012, http://me.stanford.edu/research/centers/ahpcrc/Project1_6.html.

69 “Vice President Biden Announces New Private Sector Backing for Five Pioneering Energy Companies,” *ARPA-E,* August 30, 2011, http://arpa-e.energy.gov/media/news/tabid/83/vw/1/itemid/35/vice-president-biden-announces-new-private-sector-backing-for-five-pioneering-energy-companies-.aspx; ARPA-E, *FY2010 Annual Report*.

70 ARPA-E, *FY2010 Annual Report*.

71 Jenny Wells, “CAER Receives $1.9 Million Federal Grant,” *UKNOW - University of Kentucky News*, April 30, 2010, http://uknow.uky.edu/content/caer-receives-19-million-federal-grant; ARPA-E, *FY2010 Annual Report*.

72 “General Compression,” *Cleantech Group*, accessed December 12, 2011, http://research.cleantech.com/company/general-compression/; ARPA-E, *FY2010 Annual Report*. Design photo available at, Martin LaMonica, “Start-up pumped for compressed air wind storage,” *CNET*, June 7, 2011, http://news.cnet.com/8301-11128_3-20069772-54/start-up-pumped-for-compressed-air-wind-storage/.

73 Flow batteries have two tanks with liquid electrolytes that are pumped through a membrane to create a chemical reaction that generates a flow of electricity, and ideal for grid energy storage. Martin LaMonica, “MIT flow battery breaks mold for cheap storage,” *CNET*, June 6, 2011, http://news.cnet.com/8301-11128_3-20069295-54/mit-flow-battery-breaks-mold-for-cheap-storage/.

74 “Vice President Biden Announces New Private Sector Backing for Five Pioneering Energy Companies,” ARPA-E.

75 ARPA-E, *FY2010 Annual Report*.

76 Primit Parikh, “Reimagine Power Conversion: Transphorm GaN power conversion modules,” Transphorm Inc. March 2, 2011, http://arpa-e.energy.gov/EventsWorkshops/2011InnovationSummitMaterials/Day2.aspx.

77 “Transphorm Closes $25 Million in Series D Funding,” *BusinessWire*, June 23, 2011, http://www.businesswire.com/news/home/20110623005398/en/Transphorm-Closes-25-Million-Series-Funding; “Transphorm,” *Cleantech Group*, accessed January 5, 2012, http://research.cleantech.com/company/transphorm/.

78 ARPA-E, *FY2010 Annual Report*.

79 ARPA-E, *FY2010 Annual Report*; “Biden touts OPX Bio as ARPA-E success story,” *Biofuels Digest*, September 5, 2011,

http://biofuelsdigest.com/bdigest/2011/09/05/biden-touts-opx-bio-as-arpa-e-success-story/.

80 “Gevo Supplied Isobutanol-Gasoline Blend Runs Well in Small Engines,” *Business Wire*, October 28, 2011, http://www.businesswire.com/news/home/20111028005105/en/Gevo-Supplied-Isobutanol-Gasoline-Blend-Runs-Small-Engines.

81 ARPA-E, *FY2010 Annual Report*.

82 America COMPETES Reauthorization Act of 2010, Pub. L. No. 111-358 (2011); America COMPETES Act, Pub. L. 110-69, 121 Stat. 572 (2007).

83 As of January 27, 2012, information was not yet available regarding whether this initiative had secured its desired amount in the agency's FY 2012 funding.

84 Secretary Ray Maybus, "A New Energy Future for Our Country and Our Armed Forces," *The White House Blog* (blog), *The White House*, March 9, 2011, http://www.whitehouse.gov/blog/2011/03/09/new-energy-future-our-country-and-our-armed-forces; "Hybrid Energy Storage Module," *ARPA-E*, accessed January 3, 2012, http://arpa-e.energy.gov/eventsworkshops/workshops/tabid/171/vw/3/itemid/36/d/20110519/Hybrid-Energy-Storage-Module.aspx.

85 Anthony Andrews, *Department of Defense Facilities Energy Conservation Policies and Spending* (Washington, DC: Congressional Research Service, 2009), http://www.fas.org/sgp/crs/natsec/R40111.pdf.

86 "Hybrid Energy Storage Module," *ARPA-E*, accessed January 3, 2012, http://arpa-e.energy.gov/eventsworkshops/workshops/tabid/171/vw/3/itemid/36/d/20110519/Hybrid-Energy-Storage-Module.aspx.

87 "DOE, Duke Energy, and EPRI Partner to Test Advanced Energy Technologies for Utilities," *ARPA-E*, April 12, 2011, http://arpa-e.energy.gov/media/news/tabid/83/vw/1/itemid/32/doe%2c-duke-energy-and-epri-partner-to-test-advanced-energy-technologies-for-utilities.aspx.

88 "DOE, Duke Energy, and EPRI Partner to Test Advanced Energy Technologies for Utilities," *ARPA-E*.

89 "Duke Energy," *Center for Climate and Energy Solutions*, accessed December 12, 2011, http://www.c2es.org/companies_leading_the_way_belc/company_profiles/duke%20energy.

90 "DOE, Duke Energy, and EPRI Partner to Test Advanced Energy Technologies for Utilities," *ARPA-E*.

91 Jeff Tolleson, "Risky energy research faces uncertain future," Nature, March 9, 2011, http://www.nature.com/news/2011/110309/full/471145a.html; Andrew Restuccia, "Murkowski: ARPA-E likely won't be funded at levels requested by Obama," The Hill, March 1, 2011, http://thehill.com/blogs/e2-wire/e2-wire/146685-murkowski-arpa-e-likely-wont-be-funded-at-levels-requested-by-obama.

92 Committee on Prospering in the Global Economy, *Rising Above the Gathering Storm.*

93 Jeff Tolleson, "Risky energy research faces uncertain future," Nature, March 9, 2011, http://www.nature.com/news/2011/110309/full/471145a.html; Andrew Restuccia, "Murkowski: ARPA-E likely won't be funded at levels requested by Obama," The Hill, March 1, 2011, http://thehill.com/blogs/e2-wire/e2-wire/146685-murkowski-arpa-e-likely-wont-be-funded-at-levels-requested-by-obama.

94 "At MIT, Energy Secretary Chu says he hopes ARPA-E will survive budget cuts," *Boston.com*, November 30, 2011, http://www.boston.com/business/technology/innoeco/2011/11/at_mit_energy_secretary_chu_sa.html.

95 White House, "U.S. Department of Energy," accessed February 14, 2012, http://www.whitehouse.gov/sites/default/files/omb/budget/fy2013/assets/energy.pdf.

C2ES CENTER FOR CLIMATE AND ENERGY SOLUTIONS

The Center for Climate and Energy Solutions (C2ES) is an independent nonprofit organization working to promote practical, effective policies and actions to address the twin challenges of energy and climate change.

2101 WILSON BLVD. SUITE 550 ARLINGTON, VA 22201 703-516-4146 C2ES.ORG