

Scientific, Inventive, and Market Engagement Metrics of ARPA-E Awards

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ABSTRACT

I investigate the scientific and inventive activity produced by the Advanced Research Projects Agency – Energy (ARPA-E) in its first five years of operation. Using publicly available data, I construct a novel dataset of completed energy research and development (R&D) awards given by the Department of Energy (DOE) in fiscal years 2009-2015 and the publications and patents resulting from those awards. I then compare the outputs of ARPA-E awards to those given by other offices in DOE, specifically the Office of Science and the Office of Energy Efficiency and Renewable Energy (EERE), while recognizing the differences in mission and goals among these organizations. Results of this analysis illustrate the role of ARPA-E in the landscape of DOE R&D funding. I find that: i) ARPA-E awards produce more publications and more patents compared to similar awards from the applied offices of DOE; ii) ARPA-E awards have higher rates of patenting than similar Office of Science awards, while publishing at roughly the same rate; and iii) the types of publications differ between offices, with ARPA-E awards producing energy-related publications at the same rate as EERE awards and producing high impact publications at the same rate as Office of Science awards. Separately, I examine the set of completed ARPA-E awards for variation in publishing, patenting and market engagement by different types of projects. I find that awards to universities and awards with partnerships have the greatest productivity on observable metrics. The available data indicate that ARPA-E has successfully encouraged science, invention and market engagement across a diverse set of organizations and technical programs. In its first five years, ARPA-E has been a productive component of the overall DOE R&D awards portfolio.

I. Introduction

The underinvestment of the private sector in innovation has been a subject of discussion in the economics literature for over half a century (Arrow, 1962). Firms are not able to fully capture the private benefits from innovation, and yet there are large public benefits to innovation investment. Clean energy technology innovation in particular has great potential for improving social welfare, through reduced pollution and climate impact. However, private investment in energy technology has lagged behind other sectors, due in part to the commodified nature of fuel and electricity. Scholars have recommended dramatic increases in the amount of federal funding for energy research & development (R&D) (Anadón, Bunn, & Narayanamurti, 2014; Nemet & Kammen, 2007).

Following a proposal by the National Academies in *Rising Above the Gathering Storm* (National Research Council, 2007), the Advanced Research Projects Agency – Energy (ARPA-E) was created within the Department of Energy (DOE). ARPA-E began operating in 2009 with the goal of funding technologies that could “overcome the long-term and high-risk technological barriers” and transform the energy system (110th Congress, 2007). The founding legislation for ARPA-E specifically aims to reduce uncertainty in advanced energy technology to the point that the private sector will invest.

Prior to the creation of ARPA-E, DOE had a long history of sponsoring energy research and technology development. It continues to do so through many internal organizations and funding mechanisms. The Office of Science is responsible for funding fundamental scientific research through awards to individual research projects and research centers, as well as through 10 of the 17 DOE national laboratories (U.S. Department of Energy, 2016a).¹ To support specific areas of

¹ The following labs are owned by the Office of Science: Ames Laboratory, Argonne National Laboratory, Brookhaven National Laboratory, Fermi National Accelerator Laboratory, Lawrence Berkeley National Laboratory, Oak Ridge National Laboratory, Pacific Northwest National Laboratory, Princeton Plasma Physics Laboratory, SLAC National Accelerator Laboratory, and Thomas Jefferson National Accelerator Facility.

energy technology, the DOE also contains several “applied offices”: Office of Energy Efficiency and Renewable Energy (EERE), Office of Fossil Energy, Office of Nuclear Energy, and Office of Electricity Delivery and Energy Reliability. Each of these offices coordinates R&D projects as well as deployment and maintenance for a given set of energy technologies.²

ARPA-E aims to complement the R&D activities of the six DOE offices described above, by funding “transformative research that has the potential to create fundamentally new learning curves” (ARPA-E, 2015). ARPA-E’s latest funding opportunity announcements (FOA) state that their goal is “to catalyze the translation from scientific discovery to early-stage technology.” In 2011, FOAs advised that “ARPA-E operates mainly within the ‘valley of death’ between TRL-3 and TRL-7,” referring to technology readiness levels (TRL) that range from observation of basic principles at TRL 1 to fully operating technology at TRL 9 (ARPA-E, 2011).

ARPA-E states clearly that its goal is to fund only “applied research and development of new technologies” (ARPA-E, 2014). Since 2012, every FOA has included specific instructions for applicants on determining whether their proposal is appropriate for ARPA-E:

Applicants interested in receiving financial assistance for basic research should contact the DOE’s Office of Science. Similarly, projects focused on the improvement of existing technology platforms along defined roadmaps may be appropriate for support through the DOE offices such as: the Office of Energy Efficiency and Renewable Energy, the Office of Fossil Energy, the Office of Nuclear Energy, and the Office of Electricity Delivery and Energy Reliability. (ARPA-E, 2012)

Based on this framing, it appears that ARPA-E envisions its role within DOE as a connector or an “in-between” funding source, for ideas that are transitioning from the lab (where they may have been supported by Office of Science) to the marketplace (where they may be supported by the applied offices). This concept is also depicted in the 2014 summary report by the Basic Energy Sciences within Office of Science (U.S. Department of Energy, 2014).

Only six years after they issued their first call for proposals, it is too soon to observe whether ARPA-E has contributed to transforming our energy system. Research effort and the

² Three national laboratories belong to the applied offices: National Renewable Energy Laboratory (EERE), Idaho National Laboratory (Nuclear Energy), and National Energy Technology Laboratory (Fossil Energy).

commercialization of technology take time to produce measurable outputs, and the impact of commercial projects on the energy sector takes even more time to manifest. We cannot assess whether research has led to “fundamentally new learning curves” until enough time has passed for the technology in question to mature so that its learning curve can be observed.

In this work, I assess the research productivity of ARPA-E by looking for trends in measurable outputs from ARPA-E’s projects to-date, keeping in mind the early nature of this assessment. I describe the construction of a novel dataset consisting of all completed awards given for energy-related R&D in fiscal years 2009-2015. The award data are supplemented with information on what publications and patents acknowledge these specific sources of DOE support. I use these data to compare ARPA-E to both the Office of Science and the Office of Energy Efficiency and Renewable Energy (EERE). I also compare publication, patenting and market engagement among project types within ARPA-E.

In summary, I find that in comparison with the rest of DOE, ARPA-E has high levels of scientific and inventive productivity. ARPA-E awards excel in publishing compared to the applied offices, achieving the publication rate of similar Office of Science awards. ARPA-E awards also patent frequently compared to other DOE R&D awards. Within ARPA-E, I find that the award outputs vary according to the type of organization, with university labs being the most likely to have some measurable output. I also find that awardees that partner with other organizations have a significant advantage in productivity.

In the following sections, I develop hypotheses regarding the output of ARPA-E awards. I then explain the methods of dataset construction in detail. In Section IV, I describe the results of my analysis, and in the final section I summarize and discuss the findings.

II. Hypothesis Development

My hypotheses are organized into two sections. The first considers how ARPA-E relates to other avenues of energy R&D funding within DOE; to this end, I make statistical comparisons of the outputs of ARPA-E to EERE and Office of Science. The second section concerns the heterogeneity of ARPA-E projects; here I look for trends among different organization types,

partnership structures, and technical programs.

Comparing to EERE and Office of Science

The DOE as a whole funds many different types of activities. The strongest points of comparison for ARPA-E within DOE are those that offer funding for R&D projects. No other part of DOE has the same specific mission to pursue transformational R&D in early stage energy technology; as such, the expected output of ARPA-E is different from both the scientific research in Office of Science and development of existing technology in the applied offices. My intention is not to judge the value of the awards from these offices in a competitive sense, but rather to understand ARPA-E's relative contribution to energy innovation among the rest of the DOE's R&D efforts.

Because ARPA-E positions itself between science and technology development, and because there is the greatest technology overlap with EERE among the applied offices, I choose EERE and Office of Science as the two groups for comparison for ARPA-E. Furthermore, because EERE and Office of Science are distinct in their missions and approaches, I compare them each separately to ARPA-E and do not make direct comparisons between the two.

The broad mission of EERE is “to create and sustain American leadership in the transition to a global clean energy economy” (U.S. Department of Energy, 2016b). It is important to note that, in addition to R&D, EERE also invests in technology demonstration and deployment projects. My first hypothesis is that ARPA-E awards produce more papers than EERE awards because ARPA-E's mission is more closely related to scientific research.

H1: ARPA-E's focus on early-stage R&D has caused its awards to publish more scientific publications than EERE.

The Office of Science, on the other hand, has “delivery of scientific discoveries” as a primary mission (U.S. Department of Energy, 2016a). As such, they are likely to produce different types of scientific results than the applied R&D funded by ARPA-E. For example, fundamental studies may yield fewer publications in energy-specific journals, and they may be more frequently published in top journals. I hypothesize that these differences will be apparent in the publication outputs of ARPA-E.

H2: ARPA-E's orientation between basic science and technology development has led its awards to produce different types of publications compared to Office of Science.

The patenting output of R&D funding is expected to be greatest for awardees who are working on technology development with a commercial focus. I hypothesize in H3 that ARPA-E produces more patents than Office of Science, due to their emphasis on ideas with commercial impact.

H3: ARPA-E's focus on applied R&D has caused its awards to be granted more patents than Office of Science.

Comparing Types of ARPA-E Projects

ARPA-E gives awards to a wide variety of organization types—small businesses and large businesses, startups and established companies, universities and non-profits. I expect this diversity to be reflected in the rates of publishing and patenting from these different organization types. Specifically, I anticipate that universities tend to produce more scientific publications than for-profit companies, while companies tend to produce intellectual property more than academic labs, and that these patterns will hold within the set of ARPA-E awardees.

In addition to the primary recipient, ARPA-E awards often are executed in partnership between several organizations. Given that the goal of ARPA-E is to advance new technologies toward commercialization, partnerships between organizations working in different stages of the development cycle could be valuable. I hypothesize that these partnerships have an effect on the outputs generated by an ARPA-E award.

H4: The outputs of ARPA-E awards differ both by type of organization for the project lead and by the partnership structure of the project.

ARPA-E funding is organized into groups of awards called programs. Each program is typically funded through a single solicitation, and most programs are targeted to address a particular technology area. The projects within a program run somewhat concurrently, though projects vary in length and exact start date. Because each technology area stems from a different set of research fields and feeds into different commercial markets, I expect to see significant variation in outputs among the ARPA-E programs.

H5: ARPA-E programs differ in their production of publications, patents and market engagement metrics.

III. The Data

Dataset Construction – DOE Awards

The DOE does not curate a unified source of information on the R&D projects they fund. I obtained award data from the Data Download page of USAspending.gov. Run by the Department of Treasury, USAspending.gov provides publicly accessible data on all federal awards, in accordance with the Federal Funding Accountability and Transparency Act of 2006 (U.S. Department of Treasury, 2016). I downloaded all transactions made to prime recipients of grants or “other financial assistance” from the Department of Energy in Fiscal Years 2009-2015. These transactions include grants and cooperative agreements, and they exclude contracts and loans.

The exclusion of contracts is important to note, because contracts are the primary mechanism through which DOE funds R&D at the national labs. Legally defined, contracts are used for government procurement of property or services, while grants and cooperative agreements are used to provide support to recipients, financial or otherwise (95th Congress, 1978). A cooperative agreement is different from a grant, in that it entails “substantial involvement” between the agency and the recipient. ARPA-E uses cooperative agreements as its primary mechanism of distributing funds, and so we choose grants and cooperative agreements³ as the most relevant choice for comparison to ARPA-E.

Each transaction downloaded from USAspending.gov is associated with an award ID (or award number), which is a string of up to 16 characters; most awards have multiple transactions associated with them. Award numbers begin with the prefix “DE”, followed by a two letter code indicating the office or program where the award originated.⁴ This system for assigning award numbers seems to have become standard for DOE assistance beginning in fiscal year 2009. I take

³ These two instruments are referred to in this report as “awards.”

⁴ The codes of interest are: AR = ARPA-E, SC = Office of Science, EE = Energy Efficiency and Renewable Energy, OE = Office of Electricity, NE = Office of Nuclear Energy, FE = Fossil Energy.

advantage of this system to organize the transactions by DOE office.

Many of the transactions are duplicates; therefore, the data must be processed in order to consolidate to one entry reflecting the total funding per award. Further modifications are necessary to limit the dataset to only those awards that relate to energy R&D. I am able to categorize each award based on its Catalog of Federal Domestic Assistance (CFDA) number, and I exclude those awards that are not related to R&D activities, such as block grants to city governments for energy efficiency upgrades. See Table S1 for a comprehensive list of the CFDA numbers considered here to be within the scope of energy R&D, as well as Table S2 for the codes that were excluded.

In order to arrive at a dataset containing one observation per award, and only those awards that are relate to energy R&D, the following steps were taken using the original data downloaded from USAspending.gov:

1. Duplicate transactions were removed.⁵
2. All remaining transaction amounts were summed to obtain the net federal obligation.
3. Awards were included in the dataset if they meet all of the following criteria:
 - a. Net federal obligation is positive.
 - b. Originates in one of the six offices that fund R&D (ARPA-E, Science, EERE, OE, NE, FE) based on the award number.
 - c. Award starting date is on or after Oct. 1, 2008.
 - d. Award ending date is on or before Sep. 30, 2015.⁶
 - e. Award has a CFDA number related to energy R&D.

The resulting dataset (referred to as “DOE dataset” for the remainder of this report) contains 5,896 awards, 263 of which are from ARPA-E. None of the awards from FY 2009 were from

⁵ Duplicates are identified as transactions with the same award number and same federal funding amount, and that were entered in the database in the same fiscal year. One transaction from a set of duplicates was chosen based on the following criteria, in order: most recently modified, earliest starting date for the award, and latest ending date for the award.

⁶ This restriction is loosened as a robustness check in Table S3.

ARPA-E—the first ARPA-E awards began in December 2009. EERE and Office of Science together produce a majority (80%) of the awards in the dataset. Each of the variables analyzed in this report is defined in Table 1, and the mean values are reported in Table 2. The mean and standard deviation of each variable by office are displayed in Table 3.

Publication Data

Publication outputs of DOE awards were obtained from the Web of Science (WOS), a subscription-based product from Thomson Reuters with information on scientific publications and citations. All searches in the following section were automated using the WOS API. For each award in the DOE dataset, I searched for the award number in the Funding Text field of the WOS publication records.⁷ Each search returned a list of all articles and conference proceedings (collectively referred to here as papers) that acknowledge that award number.

I downloaded bibliographic data for all papers published through Dec. 31, 2015 that acknowledge an award in the DOE dataset. Separate searches were submitted to obtain the references within each paper, as well as the citations made to each paper between April 1, 2009 and Dec. 31, 2015. The publication outputs of each award were added to the DOE dataset.

A paper-level dataset was also created of only those papers which acknowledge an award in the DOE dataset. There are 9,152 papers in this set, 56 of which jointly acknowledge two DOE offices. 561 papers acknowledge an ARPA-E award.

Additional information was downloaded from Thomson Reuters to supplement my publication analysis: *i*) a list of all indexed journals assigned to one of 22 categories, *ii*) citation thresholds for highly cited papers in each category by publication year, *iii*) a list of top journals with the number of highly cited papers published in that journal since 2005, *iv*) a list of 88 journals classified by the Science Citation Index subject category “Energy & Fuels.”

In the paper-level dataset, 9% were in journals classified as “Energy & Fuels”, 23% were in a top

⁷ The search term for WOS took the following form, e.g. *FT = AR0000001 OR FT = AR 0000001* for award DE-AR0000001. Papers that acknowledge DOE support with no award number are not included in the dataset.

journal, and 5% were highly cited for a given field and year. The most prevalent journal categories were Chemistry, Physics, Engineering or Materials Science; 71% of papers were in one of these four subjects.

Patent Data

The US Patent and Trademark Office (USPTO) maintains a publicly accessible website with full text of all issued patents since 1976,⁸ and I use these data to determine the patenting activity of DOE awards. All searches of the USPTO site were automated using an HTML web scraper. For each award in the DOE dataset, I searched for the award number in the Government Interest field of all USPTO records.⁹

I extracted the patent title, patent number, date, and number of claims from the web page of all patents granted through Dec. 31, 2015 that acknowledge an award in the DOE dataset. Separate searches were also submitted to obtain patent citations made to each of these patents through Dec. 31, 2015. The patenting outputs of each award were added to the DOE dataset.

A patent-level dataset was also created on the basis of distinct patents which acknowledge an award in the DOE dataset. There are 392 patents in this set, and 2 of the patents jointly acknowledge two DOE offices. 75 patents acknowledge an ARPA-E award.

Dataset construction – ARPA-E awards

Separately from the DOE data that were downloaded from USAspending.gov, ARPA-E provided data on their award history to the NAS Committee for the Evaluation of ARPA-E; these data were current as of September 17, 2015.¹⁰ These data are organized by project, and they include project characteristics that are specific to ARPA-E, such as which technology program funded the project. Programs that were broadly solicited across all technology areas are considered

⁸ Available at <http://patft.uspto.gov/netahtml/PTO/index.html>

⁹ The search term for USPTO took the following form, e.g. *GOVT/AR0000001 OR GOVT/"AR 0000001"* for award DE-AR0000001. Patents that acknowledge award numbers in an alternative format are not identified by the above search term and therefore are not included in the dataset.

¹⁰ Data provided are available in the public access file for the committee's report.

“open”; these are OPEN 2009, OPEN 2012 and IDEAS.¹¹

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

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

1. Remove projects with an end date on or before Sep. 30, 2015.¹²
2. Remove projects led by national labs.

First, excluding active projects allows a fair comparison between only those projects which have completed their negotiated R&D activities. The early outputs from ongoing projects, some of which had just begun at the end of FY 2015, would not accurately represent the productivity of these projects. This step has a dramatic effect on the size of the dataset—over half of the projects that had been initiated by ARPA-E as of Sep. 30, 2015 were still active at that time.

Second, I exclude national lab-led projects, which are funded by ARPA-E through work authorizations to the management and operation contract between DOE and the national lab. Many of these projects are in fact sub-projects of a parent project led by a different organization. In these cases, it is likely that the outputs of the national lab projects acknowledge the award number of the parent project, rather than the national lab contract itself.¹³ As a result, I am not

¹¹ There have been three OPEN solicitations (2009, 2012, and 2015), but only OPEN 2009 and OPEN 2012 had projects that were active during my study time period.

¹² Because this cutoff date occurred after the data were acquired from ARPA-E on Sep. 17, it is possible that some projects were extended in the meantime and were in fact still active at the start of FY 2016.

¹³ There are some exceptions. Of the 21 completed national lab-led projects, 2 have published and 6 have some form

able to accurately assess the output of the national lab-led projects individually.

The resulting dataset (“ARPA-E dataset”) contains 208 awards. The observations in the ARPA-E dataset are only a subset of the 263 ARPA-E awards in the DOE dataset. This is because ARPA-E reports data on a per-project basis, and each project may encompass multiple awards (e.g. one to the lead awardee and one to each partner). Another consequence of this difference in award-based vs. project-based accounting is that awards may have different start and end dates according to the two different data sources. For both the ARPA-E and DOE dataset, I use the stated start and end date from each data source to determine project duration and the fiscal year when the project began.

In addition to the patenting and publication data described in the previous sections, the ARPA-E dataset contains information on additional metrics on “market engagement,” as defined by ARPA-E. In a public press release on February 29, 2016, ARPA-E provided lists of projects that had achieved the following outputs: formation of a new company, private investment, government partnership, initial public offering (IPO), and acquisition (ARPA-E, 2016). I use these data as early indicators of market engagement, which is a desired outcome for ARPA-E as an organization. Statistics on all award characteristics and key output metrics for the ARPA-E dataset are listed in Table 4, including a breakdown of the different forms of market engagement and the different types of partnerships observed. Table 5 shows the ARPA-E programs in chronological order, along with the number of projects they contribute to the dataset.

IV. Results

My analysis of ARPA-E awards will be presented in two segments, corresponding to my two groups of hypotheses—first in comparison to other offices in DOE, and then on the basis of project characteristics within ARPA-E. I first compare the publication and patenting outputs of ARPA-E to EERE and Office of Science. To make these comparisons sharply, I divided the DOE dataset into two overlapping samples: one that contains ARPA-E and EERE awards, and

of market engagement.

one that contains ARPA-E and Office of Science awards. Regressions were run separately on each sample. In the second segment, I compare the outputs of ARPA-E awards from different organization types and different programs. All regressions below use a logit model unless otherwise stated.

DOE Dataset

In order to make comparisons between the various offices of DOE, it is important to account for several control variables that could impact publication and patenting. First, I control for the fiscal year in which the award was given. I also control for the amount of funding to each award. The number of awards from each office by year is shown in Figure 1, and the amount of money obligated to each office by year is shown in Figure 2. On average, ARPA-E awards are several times larger than Office of Science awards, and EERE awards are larger still. To check the accuracy of my method for obtaining net obligation per award, I compare the measured values to funding amounts obtained from separate data sources for both ARPA-E and Office of Science awards; results are shown in Table 2.¹⁴

Finally, I account for two additional variables as controls: organization type of the recipient and project duration. The proportion that went to different types of awardee is shown in Figure 3. Awards from ARPA-E and Office of Science are given in roughly similar proportions to the various awardee types: approximately 50% to for-profit companies and 40% to universities. EERE gives a somewhat larger proportion of awards to non-profits and government.

Publications—DOE Dataset

The statistics on publications by DOE awards in Table 3 show that ARPA-E has the highest rate of publishing among the three offices—44% of ARPA-E awards publish at least once, compared to 18% of EERE and 27% of Office of Science awards. The same trend is shown in Model 1 and Model 3 of Table 6, where the ARPA-E indicator has a significant and positive odds ratio with respect to publication. These models control for start year and organization type, so for project

¹⁴ The ARPA-E award data were obtained from ARPA-E as described on page 4. Office of Science awards for fiscal years 2009-2015 were downloaded from the Portfolio Analysis and Management System (PAMS) website at pamspublic.science.energy.gov. I am not aware of any similar data source for EERE awards.

given to similar entities in a similar timeframe, ARPA-E produces more publications per award than EERE awards and Office of Science awards.

The comparison with EERE is shown to be robust with additional control variables in Model 2 of Table 6; an ARPA-E award is more likely to produce a publication compared to comparable EERE awards, with an odds ratio of about 3. However, the significance of the ARPA-E odds ratio compared with Office of Science disappears with the addition of project duration and net obligation as controls (Model 4). ARPA-E awards are on average over 4 times larger in funding amount and 15% longer in duration than Office of Science awards (Table 3), both of which lead to increased odds of publishing. With the appropriate controls, it is shown that ARPA-E awards publish at a similar rate to Office of Science awards.

These results are robust to variation in model choice and sample boundaries. Table S3 shows that the above results hold for a sample of all energy R&D awards, including those that were still active at the start of FY 2016—ARPA-E awards are more likely to publish than EERE awards, and they publish at a similar rate to Office of Science awards. If I use OLS regression rather than a logit model on the DOE dataset, the same patterns emerge (Table S4).

Beyond the indicator variable for whether any papers are produced, I also consider the volume of papers produced. The incidence rate ratio of publishing for an ARPA-E award is higher than an EERE award and equivalent to an Office of Science award (Models 1 and 2 in Table S5). This was also evident from the fact that Office of Science and ARPA-E have equivalent values of mean number of publications per award in Table 2.

Apart from the statistical models, I also perform a simple calculation of the efficiency of investment in terms of how many publications were produced by each office's awards. In this dataset, the investment per publication is: \$1.1 million from ARPA-E, \$3.5 million from EERE, and \$0.2 million from Office of Science. This result reflects both the rate at which publications are produced by awards and the typical funding level of these awards; it should be considered in the context of the goals of each office and the types of activities they support.

In another check for consistency, I compare across the full DOE dataset, including all six offices

(Model 1 in Table S6). The odds ratios on all office indicators, compared to ARPA-E as the base office, are less than 1 with at least 90% confidence, meaning that ARPA-E awards are the mostly likely to produce publications of any office in DOE. Here, the odds of publishing for Office of Science awards are actually lower than ARPA-E awards (odds ratio of 0.7), though still higher than any of the applied offices.

The publication types that result from DOE awards differ among offices. ARPA-E awards tend to produce more papers in energy journals than Office of Science awards (Table 8). Meanwhile, ARPA-E awards produce papers in top journals more frequently than EERE awards, as well as highly cited papers (Table 9). In both top journal and highly cited papers, ARPA-E awards appear equivalent to their Office of Science peers.

Using the paper-level dataset, I analyze other aspects of the publications produced by ARPA-E compared to other DOE offices (Table 10). Specifically, I examine the diversity of references within a paper (i.e. how many references are to other journals vs. the same journal) and the mean age of those references in years. Indicator variables for each office show that, compared to ARPA-E, EERE produces papers with greater reference diversity, and Office of Science produces papers with less reference diversity, though both of these effects are small. The average age of references published by an award from ARPA-E is statistically similar to those from EERE and Office of Science awards. Papers from FE and NE awards tend to have significantly older references, and those from OE have newer references.

Patents—DOE Dataset

The average values of patents per award (Table 3) show that a greater proportion of ARPA-E awards (13%) produce a patent, compared to EERE (5%) or Office of Science (2%). The comparison with EERE awards remains with or without controls for project duration and net obligation (Table 7)—ARPA-E awards have 3-4 times higher odds of being granted at least one patent than EERE awards. In comparison with Office of Science, ARPA-E awards are also more likely to patent, though this effect is weakened by controlling for net obligation and project length.

When active awards are included in the sample (Table S3), I obtain the same results: ARPA-E

awards have 3 times higher odds of patenting than EERE awards and twice the odds of patenting as Office of Science awards. A positive effect on patenting relative to both EERE and Office of Science awards also results from using an OLS model on the DOE dataset (Table S4), though in this case the two effects are of the same size (8-9% higher probability of patenting for ARPA-E awards).

The patenting advantage for ARPA-E is consistent in several other specifications. In a negative binomial model for number of patents per award (Table S5), ARPA-E awards have a higher incidence rate ratio for patenting than both EERE and Office of Science awards. And with a sample that includes all DOE offices (Model 2 in Table S6), the odds ratios on all office indicators are less than 1 within 99% confidence;¹⁵ ARPA-E is far more likely to produce a patent than any of the other offices.

The regression coefficients in Table 7 show that award length and amount are both associated with the likelihood of patenting. As was the case with publications, larger funding amounts lead to more patenting on average. Interestingly, the control for project duration works in the opposite direction—longer projects are less likely to patent.

In the same way that I calculated the efficiency of publications, I also calculate the efficiency of each office's investment in terms of dollars per patent. Those values are as follows for the awards in this dataset: \$8.2 million from ARPA-E, \$28.4 million from EERE, and \$18.1 million from Office of Science.

I check for patent quality among the various offices by asking whether a patent has been cited by other patents, while noting that patent citation is a rare outcome in this dataset, due in part to the time lag in the patenting process. I find that ARPA-E has significantly higher odds of producing a cited patent than EERE (Model 3 of Table 9).¹⁶ Another measure of patent quality is in the

¹⁵ With the exception of NE, which was dropped from the logit model for having produced no patents, and thus has no variation in PATENT DUMMY.

¹⁶ Only 5 awards (< 0.2%) from Office of Science produced a cited patent. The logit model reported in Table 9 was not able to converge for the sample of awards from ARPA-E and Office of Science.

number of claims—in Model 3 of Table 10, I find that patents from the other DOE offices have significantly fewer claims than those from ARPA-E.

Publishing and Patenting—ARPA-E Dataset

While the regression results to follow deal with the average rates of publishing and patenting among various groups, it is interesting to note a small set of awards with unusually high rates of project output. First, I find that one award notably excelled in scientific publications. An award made in 2010 from the IMPACCT program to Texas A&M University led by Professor Hongcai Zhou (DE-AR0000073) had the most publications of any ARPA-E award: 41 papers total. This award was for the study of metal organic frameworks for CO₂ storage, and it was also an outlier in terms of citedness. Eight of the top 10 most cited papers in ARPA-E history acknowledge this award, and in fact the most cited paper from this award was a 2012 *Chemical Reviews* article that received the most citations of any in my entire DOE paper-level dataset (1673 citations through Dec. 31, 2015). The next highest number of publications for an ARPA-E award came from a 2012 award in the MOVE program for methane storage in porous materials, also led by Professor Zhou (DE-AR0000249). This award was acknowledged by 23 papers, one of which was shared with the earlier award to the same group.

There is also an outlier in terms of patenting outputs from ARPA-E awards. The award with the greatest number of patents was made to Foro Energy through the OPEN 2009 program (DE-AR0000044) to develop laser drilling technology for enhanced geothermal or natural gas. This award was acknowledged by 15 patents during the study period, 7 of which have been cited by other patents. Meanwhile, the ARPA-E patent that has received the greatest number of citations acknowledges two awards made to Makani Power (DE-AR0000122 and DE-AR0000243) from the OPEN 2009 program; this patent has itself been cited by 8 patents through the end of 2015.

I now turn to a systematic comparison of publishing and patenting outputs within the ARPA-E dataset. In these regressions, I use a similar set of controls as were used in the previous subsection using the DOE dataset, with two modifications. First, I replace the start year fixed effect with a fixed effect for the technical program through which a project was funded. This cohort effect accounts for both the technology area and the time period when a project began.

The second change is the addition of a binary variable for whether or not the project was listed with any partnerships.

I find that organizations of different types do perform differently as ARPA-E awardees (Table 11). Within ARPA-E, awards to universities produce publications significantly more often than awards to both established and startup companies. The standard errors on patenting are too high to establish any significant trend across either different org. types or partnership status. However, it is clear that funding amount has a large effect on patenting outputs, as it did in the DOE dataset.

Another way to look at the publishing and patenting success of ARPA-E projects is to compare the extent of publishing and patenting within each program. These are plotted as percent of completed projects that have published (Figure 4) and percent that have patented (Figure 5) as of Dec. 31, 2015. The programs are listed in chronological order; many projects from early programs have published, and there is a sharp drop off for those programs that started in FY 2014. The effect over time is apparent for patenting outputs as well, as the greatest rates of patenting so far are from programs that started in FY 2010.

Several programs have had publications from over half of their completed projects; the highest proportion of projects that published comes from the Electrofuels and IMPACCT programs. Patenting is a less frequent outcome than publishing; only the BEEST program has had patents granted to over half of its completed projects. Table 12 displays the odds ratios of publishing and patenting for each program relative to OPEN 2009, with controls for organization type, partnership status, project duration, and funding amount.

Market Engagement—ARPA-E Dataset

I now compare the outputs of ARPA-E awards on several market engagement metrics: private investment, government partnerships, company formation, IPOs, acquisitions, and commercial products. Each of these outputs is most relevant for a different set of ARPA-E awardees—64% of awards with private funding were to startup companies, 78% of the awards with government partnerships were to companies, and most of the awards that spun out companies were to

universities.¹⁷

I combine the six outputs above into a single market engagement metric, indicating success in at least one of the outputs above; 74 projects in the dataset (36%) have achieved this metric.

Results from Model 3 in Table 11 point to startup companies as the ARPA-E awardees most likely to engage the market in an observable way. Comparing this metric across programs, the PETRO program stands out as having market engagement for 100% of its completed projects (Figure 6), though this results is derived from a small sample of only two projects—one that formed a new company and one with an IPO.

Combined Metrics—ARPA-E Dataset

Given the assessment above of all these outputs (papers, patents, and market engagement metrics), I ask whether there are any trends in project output that span multiple metrics. One way to compare outputs is to analyze whether a project has had at least one observable indicator of success from any of the outputs measured. 143 projects in the dataset (69%) have at least one observable output; the proportion of projects in each program that meet this standard is plotted in Figure 7. The IMPACCT and GRIDS programs have had some measurable output for 100% of their completed projects.

Table 11 (Model 4) shows that established companies are least likely to produce an observable output from their ARPA-E award. These results also show that having a partnership makes a project much more likely to achieve success in at least one external metric. Both of these findings are robust to using an OLS model rather than logit (Model 4 in Table S7).

An additional metric of project performance is whether the project has achieved each of the three outputs measured: at least one publication, at least one patent, *and* at least one form of market engagement. There are 9 projects in the dataset (4%) that have had all three outputs. Five of these projects are related to batteries: 4 from the BEEST program, and one from OPEN 2009.

¹⁷ ARPA-E counts some awards to startup companies in its list of projects that resulted in company formation. These are companies which received their first funding through an ARPA-E award.

V. Discussion & Conclusion

During its first five years of operation (FY 2010-2015), ARPA-E awards have been directly acknowledged in at least 561 papers and 75 patents. Over one third of completed projects have been reported by ARPA-E as having some market engagement success, such as private funding or company formation. My analysis in the previous section quantifies the productivity of ARPA-E's research efforts in terms of scientific and inventive outputs, using other DOE awards and groups of awards within ARPA-E as the bases for comparison. In this section, I address each of the hypotheses from Section II in turn and discuss possible interpretation of the results.

I find that ARPA-E awards publish scientific papers frequently compared to the applied offices of DOE, when controlling for project length, funding amount, project start year, and awardee type, thus confirming hypothesis H1. The focus of ARPA-E on early-stage technology R&D makes it more likely to fund projects which produce scientific publications, compared to organizations like EERE which emphasize development of more mature technology. However, ARPA-E awards publish at roughly the same rate as similar Office of Science awards, despite that organization's strong focus on the production of fundamental science. ARPA-E's orientation toward applied research has apparently not prevented their awardees from producing scientific discoveries at a significant rate.

Overall, ARPA-E awards produce a significant volume of papers in both energy-related journals and high-quality journals, and the papers they produce are highly cited. Hypothesis H2 is confirmed, as I find that ARPA-E awards publish more frequently in energy journals than Office of Science awards. However, ARPA-E awards are no less likely than Office of Science awards to publish highly cited and top-journal papers. Meanwhile, compared to EERE awards, ARPA-E awards are just as likely to publish in energy journals, and they are more likely to publish top-journal and highly cited papers. Again, rather than being positioned between the two offices in these metrics, ARPA-E either outperforms or matches the performance of each office.

In terms of patenting, I find that ARPA-E awards produce patents more frequently than the rest of DOE, when controlling for key award characteristics. Though they patent at only a slightly higher rate than similar Office of Science awards, the patents they produce are much more likely

to be cited by other patents, indicating that the patents are either higher quality, relevant to a later stage of technology development, or both. This result confirms hypothesis H3. In fact, my results demonstrate an even greater degree of patenting success than expected for ARPA-E, in that they patent more frequently than comparable EERE awards. This may be due to ARPA-E's focus on early-stage technology projects, where awardees are likely to generate intellectual property as part of their research activities, compared to projects that improve existing technologies.

Turning to comparisons within ARPA-E, I am able to confirm the first aspect of hypothesis H4, by showing that the types of outputs produced by ARPA-E awards vary by the type of organization that leads the project. Projects led by universities, unsurprisingly, are more likely to publish. In fact, considering all the measured outputs in total, awards to universities are the most likely to have produced any output. Meanwhile, awards to startups are most likely to yield measurable market engagement, and awards to established companies are the most likely to have yielded no measurable output.

One explanation for the reduced outputs measured from awards to established firms is that these companies are likely to choose to protect the scientific information they produce, rather than share it publicly as an academic lab would. Furthermore, established companies can pursue technology development internally following success of a project, while startups must seek external funding to continue their R&D work. Internal support product development, in that it represents a kind of private sector investment, meets ARPA-E's stated goal of advancing technology to the point that the private sector will invest. However, without access to data on this process, then I cannot fairly measure the success of awards to established companies.

I find that having a partnership between the lead recipient and another organization makes an award significantly more likely to yield some measure of success. This confirms the second aspect of hypothesis H4, though I cannot tell from my analysis if this effect is causal.

Partnerships could be beneficial to ARPA-E awardees' productivity in several ways. For example, partnerships with universities likely help non-academic awardees produce publications, and partnerships with companies could ease the transition to engaging the market for academic and non-profit labs. An alternative explanation is that higher quality projects and teams attract partnership from the start. Perhaps awardees with the propensity to succeed are more likely to

pursue partnerships, or partners are more likely to sign on to projects that they perceive are likely to succeed. I cannot rule out any of the above explanations with the data available, though it is clear that the effect of partnerships warrants further study.

The final question I address is that of comparing the outputs of the various technical programs in ARPA-E's history. It is apparent from the progression of outputs over time (Figure 4, for example) that hypothesis H5 is literally correct, in that these programs have produced different levels of various outputs. A majority of the measured outputs were produced by early ARPA-E programs (FY 2012 or before). While it is reasonable to ask whether ARPA-E programs have changed in terms of productivity over time, the answer is not apparent from my data for two reasons. First, and most importantly it is too early to observe a full set of outputs from many of these projects, especially for patents, which can take several years to be granted after the initial application. And second, my ARPA-E dataset contains only awards that had reached their end date by the start of FY 2016. For the most recent programs, the projects that have already been completed are shorter in duration than the active projects, and shorter projects are more likely to have been terminated before their originally negotiated end date. Conversely, projects with early indicators of success may have been extended and therefore do not appear in my data.¹⁸ This effect biases my results toward a conservative measurement of project success.

To conclude, I have studied the set of completed R&D awards given by DOE in FY 2009-2015, and I find that ARPA-E awards have been productive in both publishing and patenting compared to similar awards in other offices of DOE. The rate of scientific publishing from ARPA-E awards roughly matches that of Office of Science awards, and the rate of patenting exceeds that of the R&D awards given by other offices of DOE, including the applied programs. These comparisons were made accounting for the logarithmic effects of project duration and funding amount, as well as fixed effects for the project start year and the type of organization. Based on ARPA-E's self-description, they are oriented somewhat between fundamental science and technology, and yet they perform as well or better than the other DOE offices in producing measurable outputs of

¹⁸ See Goldstein and Kearney (2016) for further discussion of both the time lag in outputs and project length changes as a facet of active management in ARPA-E.

science and innovation.

Furthermore, I find that the outputs of the ARPA-E awards completed to-date reflect the diverse nature of the organizations funded by ARPA-E. Over one third of awardees have made progress toward marketing their technology, though there is limited data availability on continued technology development within an established firm. The strongest association with measurable success for an ARPA-E award is whether or not the project was carried out as a partnership between multiple organizations. At the time of this writing, there are as many active projects as completed projects, and even those completed projects may have outputs that are not yet included in public data sources. The conclusions reached here are based heavily on data from the first two years of ARPA-E funding; future attempts to evaluate ARPA-E will benefit from a longer timespan for outputs to accumulate.

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Table 1 – Variables & Definitions

| Variable | Definition |
|-------------------------------------|---|
| DOE Award Characteristics | |
| Office | 3 distinct DOE awarding offices (ARPA-E, EERE, Office of Science) |
| Ln(Project Duration) | Natural log of the number of years from start date to end date of an award |
| Ln(Net Obligation) | Natural log of the net federal obligation amount in millions USD |
| Start Year | 6 fiscal years of award start dates (2009-2015) |
| Org. Type | 5 distinct categories of awardee (Higher Ed., Non-Profit, For-Profit, Government, Other) |
| ARPA-E Award Characteristics | |
| Program | 28 distinct groups of projects with either a particular technology focus or as one of several open solicitations |
| Org. Type | 4 distinct categories of awardee (Higher Ed., Non-Profit, Established Company, Startup Company) |
| Partnership | 1 if a project is in partnership with another organization; 0 otherwise |
| Publication Metrics | |
| Publication Count | Number of papers acknowledging an award |
| At Least 1 Publication | 1 if Publication Count > 0; 0 otherwise |
| Energy Journal | 1 if an award was acknowledged in a journal from the “Energy & Fuels” category; 0 otherwise |
| Top Journal | 1 if an award was acknowledged in one of the top 40 journals in order of highly cited papers published 2005-2015; 0 otherwise |
| Highly Cited Publication | 1 if an award was acknowledged in the top 1% of highly cited papers in the same research field and the same year; 0 otherwise |
| Reference Diversity | Fractional percentage of cited references in a paper made to works other than the publishing journal (ranging from 0 to 1). ¹⁹ |
| Avg. Reference Age | Mean age (years from the date of publication) of cited references in a paper |

¹⁹ This is an upper bound due to possible missed matches from different journal abbreviations.

Table 1 continued – Variables & Definitions

| Patenting Metrics | |
|---|---|
| Patent Count | Number of patents acknowledging an award |
| At Least 1 Patent | 1 if Patent Count > 0; 0 otherwise |
| Cited Patent | 1 if an award was acknowledged by at least one patent that was itself cited by another patent; 0 otherwise |
| Avg. Number of Claims | Mean number of claims in patents that acknowledge an award |
| Market Engagement and Combined Metrics | |
| Private Funding | 1 if a project received private funding according to ARPA-E; 0 otherwise |
| Public Funding | 1 if a project received government funding or formed a public partnership according to ARPA-E; 0 otherwise |
| Company Formation | 1 if a project resulted in formation of a company or if the ARPA-E award was the first funding for a startup awardee; 0 otherwise |
| Market Engagement | 1 if an award has any form of market engagement: private funding, public funding, company formation, IPO, acquisition, or commercial product; 0 otherwise |
| Any Output | 1 if the project resulted in a publication, a patent, or any form of market engagement metrics; 0 otherwise |

Table 2 – Summary Statistics – DOE Dataset

| Variable | Overall Sample (N = 5896) | |
|---|------------------------------|-------|
| | Mean | S.D. |
| Metrics | | |
| Publication Count | 1.63 | 8.83 |
| At Least 1 Publication | 0.24 | 0.43 |
| Energy Journal | 0.05 | 0.22 |
| Top Journal | 0.07 | 0.25 |
| Highly Cited Publication | 0.04 | 0.18 |
| Patent Count | 0.07 | 0.58 |
| At Least 1 Patent | 0.03 | 0.17 |
| Cited Patent | 0.01 | 0.08 |
| Award Characteristics | | |
| Project Duration (years) | 2.46 | 1.41 |
| Net Obligation (million USD) | 2.08 | 11.08 |
| Percent Error – Net Obligation (ARPA-E only) | -2.73 | 26.47 |
| Percent Error – Net Obligation (Office of Science only) | -0.43 | 12.79 |

Table 3 – Comparison of Means for ARPA-E, EERE and Office of Science

| Variable | ARPA-E (N = 263) | | EERE (N = 1527) | | | Office of Science (N = 3218) | | |
|------------------------------|---------------------|------|--------------------|-------|-------------------------------------|---------------------------------|-------|---|
| | Mean | S.D. | Mean | S.D. | <i>t-test</i> (ARPA-E – EERE) | Mean | S.D. | <i>t-test</i> (ARPA-E – Office of Science) |
| Metrics | | | | | | | | |
| Publication Count | 2.18 | 4.30 | 0.91 | 4.31 | 4.40 | 2.16 | 11.41 | 0.06 |
| At Least 1 Publication | 0.44 | 0.50 | 0.18 | 0.38 | 8.21 | 0.27 | 0.44 | 5.49 |
| Energy Journal | 0.15 | 0.36 | 0.08 | 0.27 | 3.05 | 0.02 | 0.14 | 5.89 |
| Top Journal | 0.18 | 0.38 | 0.04 | 0.19 | 5.83 | 0.09 | 0.28 | 3.74 |
| Highly Cited Publication | 0.10 | 0.30 | 0.03 | 0.16 | 4.02 | 0.04 | 0.20 | 3.20 |
| Patent Count | 0.29 | 1.18 | 0.11 | 0.74 | 2.40 | 0.03 | 0.34 | 3.62 |
| At Least 1 Patent | 0.13 | 0.33 | 0.05 | 0.22 | 3.54 | 0.02 | 0.13 | 5.28 |
| Cited Patent | 0.03 | 0.18 | 0.01 | 0.11 | 1.94 | 0.00 | 0.04 | 2.90 |
| Award Characteristics | | | | | | | | |
| Project Duration (years) | 2.47 | 1.08 | 2.75 | 1.22 | -3.93 | 2.14 | 1.45 | 4.56 |
| Net Obligation (million USD) | 2.39 | 1.89 | 3.20 | 11.39 | -2.59 | 0.52 | 1.17 | 15.79 |

Table 4 – Summary Statistics – ARPA-E Dataset

| Variable | Overall Sample (N = 183) | |
|------------------------------|-----------------------------|-------------|
| | <i>Mean</i> | <i>S.D.</i> |
| Metrics²⁰ | | |
| At Least 1 Publication | 0.47 | 0.50 |
| At Least 1 Patent | 0.14 | 0.35 |
| Market Engagement | 0.36 | 0.48 |
| Private Funding | 0.15 | 0.36 |
| Public Funding | 0.17 | 0.38 |
| Company Formation | 0.10 | 0.30 |
| Any Output | 0.69 | 0.47 |
| Award Characteristics | | |
| Project Duration (years) | 2.62 | 1.03 |
| Net Obligation (million USD) | 2.63 | 1.86 |
| Partnership | 0.70 | 0.46 |
| University Partner | 0.37 | 0.48 |
| Private Partner | 0.46 | 0.50 |
| Government Partner | 0.20 | 0.40 |

²⁰ Statistics for publication and patenting rates from ARPA-E awards differ slightly here from those listed in Table 3 because they come from the ARPA-E dataset, as described in Section III. Other publication and patenting metrics are omitted for brevity.

Table 5 – ARPA-E Program Information

| Program | Fiscal Year Start²¹ | N |
|----------------|---------------------------------------|----------|
| OPEN 2009 | 2010 | 37 |
| BEEST | 2010 | 10 |
| Electrofuels | 2010 | 12 |
| IMPACCT | 2010 | 13 |
| ADEPT | 2010 | 14 |
| BEETIT | 2010 | 15 |
| GRIDS | 2010 | 10 |
| HEATS | 2012 | 11 |
| Solar ADEPT | 2012 | 6 |
| PETRO | 2012 | 2 |
| REACT | 2012 | 10 |
| GENI | 2012 | 9 |
| MOVE | 2012 | 6 |
| AMPED | 2013 | 5 |
| SBIR 2012 | 2013 | 5 |
| OPEN 2012 | 2013 | 18 |
| RANGE | 2014 | 10 |
| METALS | 2014 | 5 |
| REMOTE | 2014 | 3 |
| SWITCHES | 2014 | 2 |
| IDEAS | 2014 | 3 |
| FOCUS | 2014 | 2 |

²¹ The fiscal year listed is the earliest start for any project in a given program. Though some projects from earlier programs began in FY 2011, no new programs were launched that year.

Table 6 – Odds Ratio of Producing a Publication: ARPA-E vs. EERE and Office of Science

| Model | 1 | 2 | 3 | 4 |
|------------------------------|------------------------|---------------------|----------------------------|---------------------|
| Dependent Variable | At Least 1 Publication | | | |
| Sample | ARPA-E & EERE | | ARPA-E & Office of Science | |
| Award Characteristics | | | | |
| ARPA-E | 4.285*** (0.761) | 3.612*** (0.654) | 3.607*** (0.576) | 1.151 (0.198) |
| Ln(Project Duration) | | 1.278 (0.214) | | 1.900*** (0.217) |
| Ln(Net Obligation) | | 1.372*** (0.072) | | 1.602*** (0.074) |
| Start Year Fixed Effect | Y | Y | Y | Y |
| Org. Type Fixed Effect | Y | Y | Y | Y |
| Regression Statistics | | | | |
| Observations | 1790 | 1790 | 3473 | 3473 |
| Pseudo R2 | 0.194 | 0.219 | 0.190 | 0.278 |

Sample: Completed awards with R&D-related CFDA number

Exponentiated coefficients; Standard errors in parentheses

Logit regression with robust SE

* p < 0.1, ** p < 0.05, *** p < 0.01

Table 7 – Odds Ratio of Producing a Patent: ARPA-E vs. EERE and Office of Science

| Model | 1 | 2 | 3 | 4 |
|------------------------------|---------------------|---------------------|----------------------------|---------------------|
| Dependent Variable | At Least 1 Patent | | | |
| Sample | ARPA-E & EERE | | ARPA-E & Office of Science | |
| Award Characteristics | | | | |
| ARPA-E | 4.519*** (1.216) | 3.790*** (1.012) | 14.936*** (4.193) | 2.417*** (0.809) |
| Ln(Project Duration) | | 0.580*** (0.118) | | 0.398*** (0.078) |
| Ln(Net Obligation) | | 1.725*** (0.130) | | 3.278*** (0.430) |
| Start Year Fixed Effect | Y | Y | Y | Y |
| Org. Type Fixed Effect | Y | Y | Y | Y |
| Regression Statistics | | | | |
| Observations | 1657 | 1657 | 3453 | 3453 |
| Pseudo R^2 | 0.133 | 0.186 | 0.164 | 0.253 |

Sample: Completed awards with R&D-related CFDA number

Exponentiated coefficients; Standard errors in parentheses

Logit regression with robust SE

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 8 – Odds Ratio of Producing a Publication of a Particular Type: ARPA-E vs. EERE and Office of Science

| Model | 1 | 2 | 3 | 4 |
|------------------------------|---------------------|----------------------------|---------------------|----------------------------|
| Dependent Variable | Energy Journal | | Top Journal | |
| Sample | ARPA-E & EERE | ARPA-E & Office of Science | ARPA-E & EERE | ARPA-E & Office of Science |
| Award Characteristics | | | | |
| ARPA-E | 1.462 (0.365) | 2.962*** (0.976) | 5.160*** (1.431) | 0.934 (0.230) |
| Ln(Project Duration) | 2.038*** (0.473) | 1.247 (0.400) | 1.490 (0.425) | 1.864*** (0.347) |
| Ln(Net Obligation) | 1.438*** (0.096) | 2.566*** (0.295) | 1.558*** (0.140) | 1.841*** (0.132) |
| Start Year Fixed Effect | Y | Y | Y | Y |
| Org. Type Fixed Effect | Y | Y | Y | Y |
| Regression Statistics | | | | |
| Observations | 1749 | 3473 | 1593 | 3466 |
| Pseudo R^2 | 0.167 | 0.261 | 0.186 | 0.244 |

Sample: Completed awards with R&D-related CFDA number

Exponentiated coefficients; Standard errors in parentheses

Logit regression with robust SE

* p < 0.1, ** p < 0.05, *** p < 0.01

Table 9 – Odds Ratio of Producing a Cited Publication or Patent: ARPA-E vs. EERE and Office of Science

| Model | 1 | 2 | 3 |
|------------------------------|--------------------------|----------------------------|---------------------|
| Dependent Variable | Highly Cited Publication | | Cited Patent |
| Sample | ARPA-E & EERE | ARPA-E & Office of Science | ARPA-E & EERE |
| Award Characteristics | | | |
| ARPA-E | 3.477*** (1.112) | 0.960 (0.303) | 3.671*** (1.651) |
| Ln(Project Duration) | 1.548 (0.505) | 2.103*** (0.564) | 0.406*** (0.136) |
| Ln(Net Obligation) | 1.415*** (0.169) | 2.066*** (0.207) | 1.706*** (0.212) |
| Start Year Fixed Effect | Y | Y | Y |
| Org. Type Fixed Effect | Y | Y | Y |
| Regression Statistics | | | |
| Observations | 1501 | 3466 | 1238 |
| Pseudo R^2 | 0.164 | 0.223 | 0.155 |

Sample: Completed awards with R&D-related CFDA number
 Exponentiated coefficients; Standard errors in parentheses
 Logit regression with robust SE
 * p < 0.1, ** p < 0.05, *** p < 0.01

Table 10 – OLS Model for Publication and Patent Characteristics

| Model | 1 | 2 | 3 |
|------------------------------|-------------------------------|-------------------------------|--------------------------|
| Sample | Publications from DOE dataset | Publications from DOE dataset | Patents from DOE dataset |
| Dependent Variable | Reference Diversity | Avg. Reference Age | Avg. Number of Claims |
| Sponsoring Office | | | |
| EERE | 0.015*** (0.005) | -0.176 (0.245) | -13.208*** (3.825) |
| Office of Science | -0.011** (0.005) | 0.214 (0.218) | -10.831*** (3.885) |
| OE | -0.010 (0.019) | -1.208* (0.630) | -11.629*** (4.012) |
| FE | 0.001 (0.006) | 2.257*** (0.311) | -11.940*** (3.907) |
| NE | -0.008 (0.016) | 4.798*** (0.903) | -- |
| Regression Statistics | | | |
| Observations | 9148 | 9148 | 392 |
| R^2 | 0.007 | 0.017 | 0.083 |

Standard errors in parentheses

Base office is ARPA-E

OLS regression with robust SE

* p < 0.1, ** p < 0.05, *** p < 0.01

Table 11 – Odds Ratio of Producing Outputs: ARPA-E Award Characteristics

| Model | 1 | 2 | 3 | 4 |
|------------------------------|------------------------|---------------------|---------------------|---------------------|
| Dependent Variable | At Least 1 Publication | At Least 1 Patent | Market Engagement | Any Output |
| Organization Type | | | | |
| Non-Profit | 0.095** (0.106) | 3.136 (4.548) | 1.500 (1.325) | 0.317 (0.314) |
| Established Company | 0.124*** (0.049) | 1.564 (0.613) | 1.337 (0.461) | 0.196*** (0.088) |
| Startup Company | 0.063*** (0.039) | 1.303 (1.591) | 9.950*** (5.930) | 0.545 (0.343) |
| Award Characteristics | | | | |
| Partnership | 2.880 (2.053) | 1.433 (1.229) | 1.750 (0.796) | 4.540*** (1.598) |
| Program Fixed Effect | Y | Y | Y | Y |
| Ln(Project Duration) | 0.842 (0.781) | 0.118 (0.163) | 5.111 (6.375) | 1.343 (1.103) |
| Ln(Net Obligation) | 1.545 (0.478) | 6.827*** (4.788) | 1.271 (0.432) | 1.886 (0.843) |
| Regression Statistics | | | | |
| Observations | 192 | 119 | 195 | 172 |
| Pseudo R^2 | 0.265 | 0.236 | 0.211 | 0.228 |

Sample: Completed ARPA-E awards (minus national labs)

Exponentiated coefficients; Standard errors in parentheses

Logit regression with robust SE clustered by program

Base org. type is Higher Ed.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 12 – Odds Ratios of Each Output: ARPA-E Program Fixed Effects

| Program | Dependent Variable | | | |
|--------------|------------------------|---------------------|-----------------------|---------------------|
| | At Least 1 Publication | At Least 1 Patent | Market Engagement | Any Output |
| ADEPT | 1.062 (0.375) | 0.556*** (0.092) | 0.707 (0.166) | 0.208*** (0.043) |
| AMPED | 1.822 (0.789) | 1.021 (0.515) | 0.757 (0.292) | 0.532* (0.201) |
| BEEST | 1.785*** (0.157) | 3.616*** (0.994) | 1.740*** (0.371) | 0.285*** (0.039) |
| BEETIT | 0.750 (0.134) | All 0 | 1.306 (0.297) | 0.333*** (0.081) |
| Electrofuels | 2.392** (0.853) | 0.679 (0.241) | 0.308*** (0.115) | 0.557 (0.224) |
| FOCUS | All 0 | All 0 | 13.316*** (10.429) | 0.385 (0.227) |
| GENI | 0.626 (0.191) | 0.247*** (0.045) | 1.338 (0.260) | 0.199*** (0.039) |
| GRIDS | 2.025*** (0.167) | 0.298*** (0.054) | 2.539*** (0.418) | All 1 |
| HEATS | 1.847*** (0.370) | All 0 | 0.158*** (0.054) | 0.216*** (0.045) |
| IMPACCT | 4.756*** (1.228) | 1.102 (0.125) | 2.537*** (0.547) | All 1 |
| MOVE | 4.234*** (2.031) | All 0 | 1.260 (0.450) | 0.947 (0.293) |
| OPEN 2012 | 0.336*** (0.113) | All 0 | 1.187 (0.625) | 0.157*** (0.076) |
| PETRO | 0.619 (0.373) | All 0 | All 1 | All 1 |
| RANGE | 0.702 (0.311) | All 0 | 0.597 (0.392) | 0.290* (0.198) |
| REACT | 1.226 (0.295) | 0.419*** (0.087) | 2.266*** (0.512) | 0.515* (0.180) |
| REMOTE | All 0 | All 0 | 3.839 (3.435) | 0.425 (0.413) |
| SBIR 2012 | 0.681* (0.135) | All 0 | 0.626* (0.156) | 0.314*** (0.069) |
| Solar ADEPT | 1.386 (0.317) | All 0 | 0.348** (0.166) | 0.250*** (0.063) |

Fixed effects come from models in Table 11. Lack of variation prevented estimation of some fixed effects.

IDEAS, METALS and SWITCHES are not included due to lack of measured outputs.

Base program is OPEN 2009. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Figure 1 – Number of Awards from Different Offices by Year

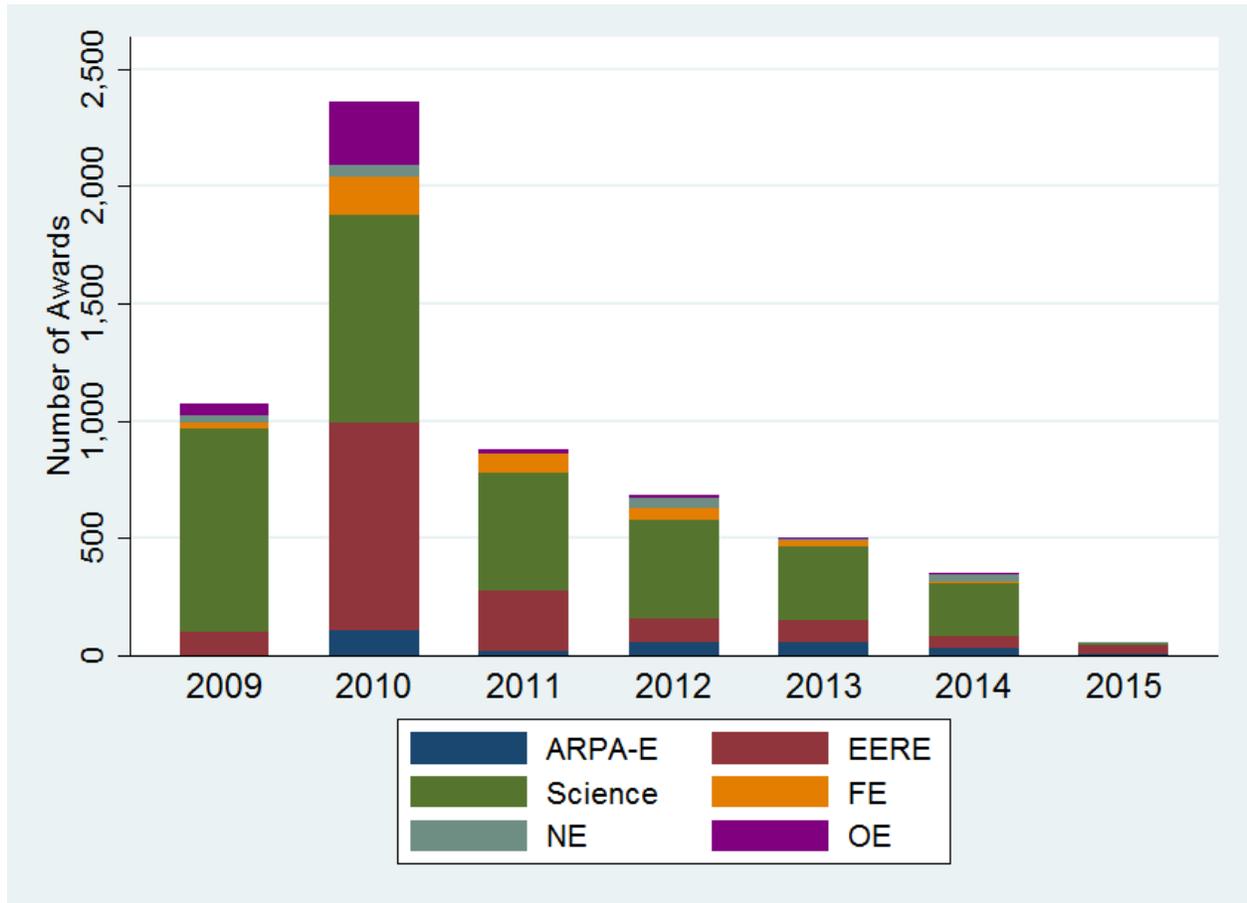


Figure 2 – Award Amounts from Different Offices by Year

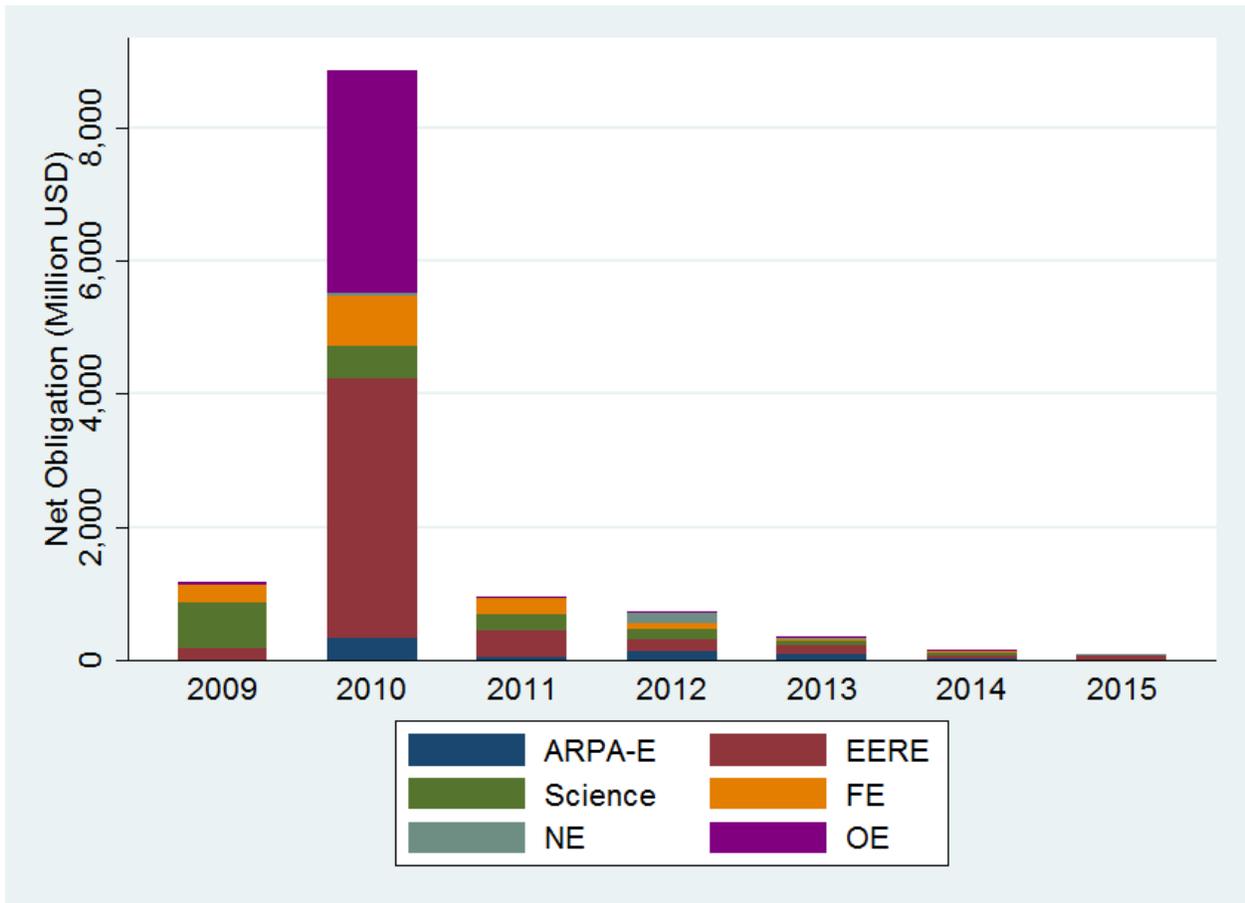


Figure 3 – Proportion of Awards to Different Org. Types by Office

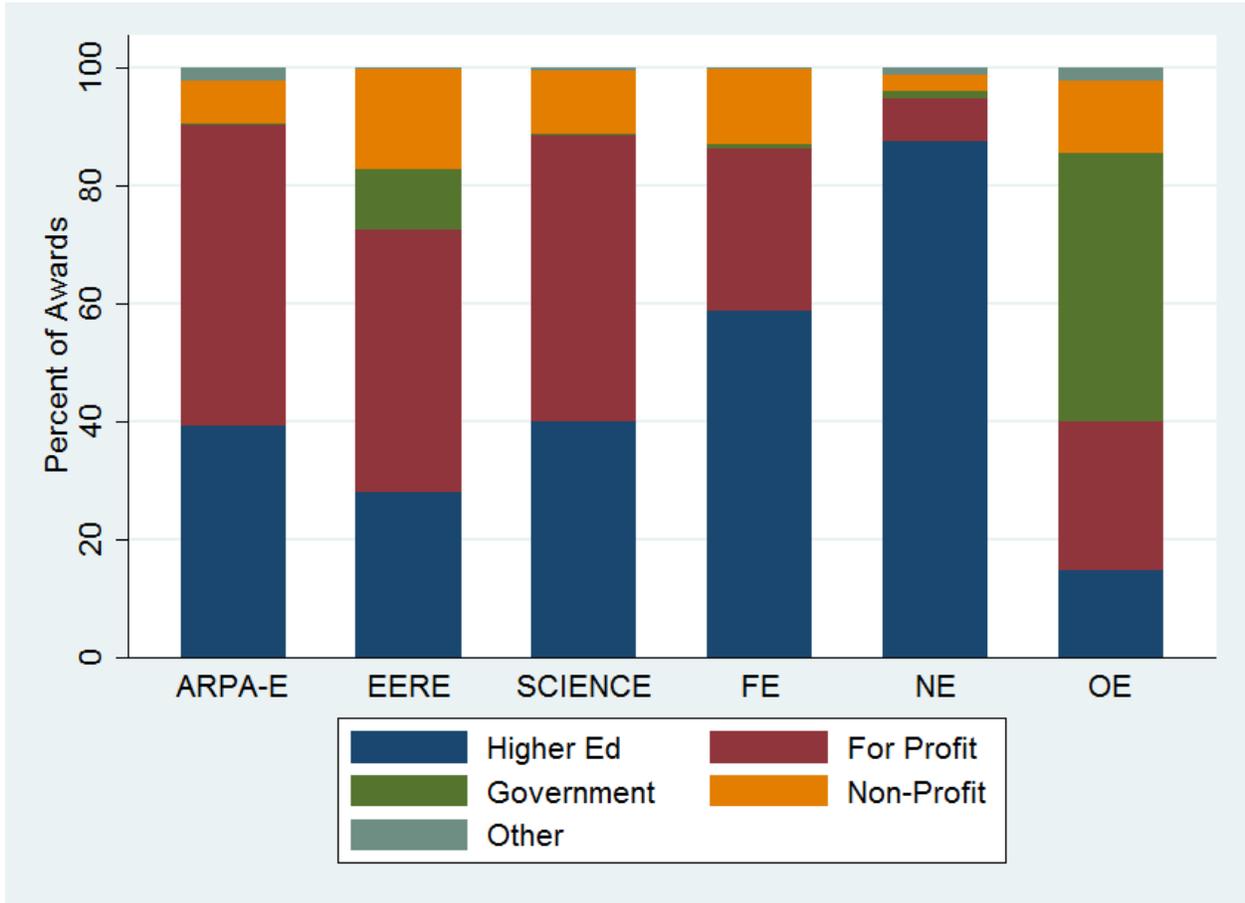


Figure 4 – Publishing by ARPA-E Programs

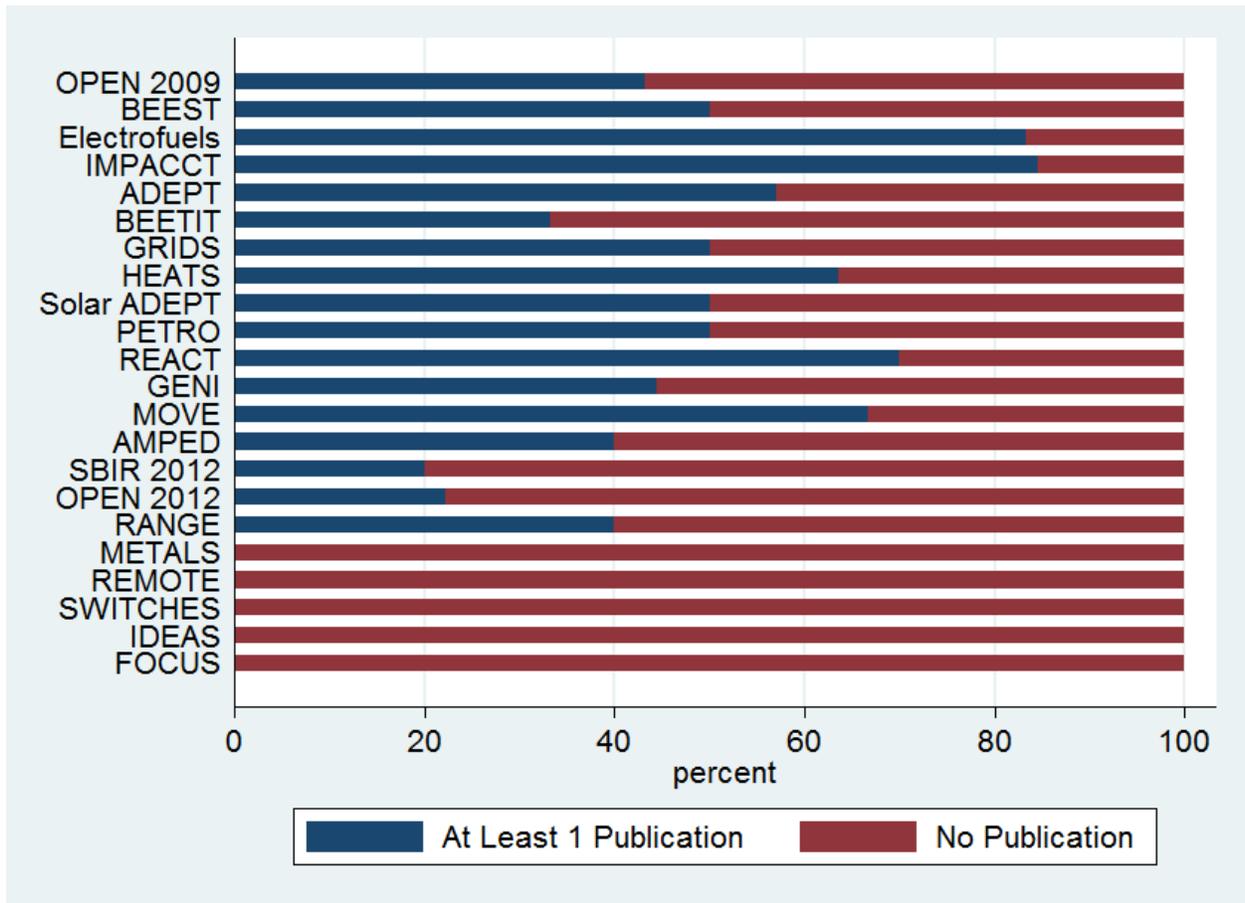


Figure 5 – Patenting by ARPA-E Programs

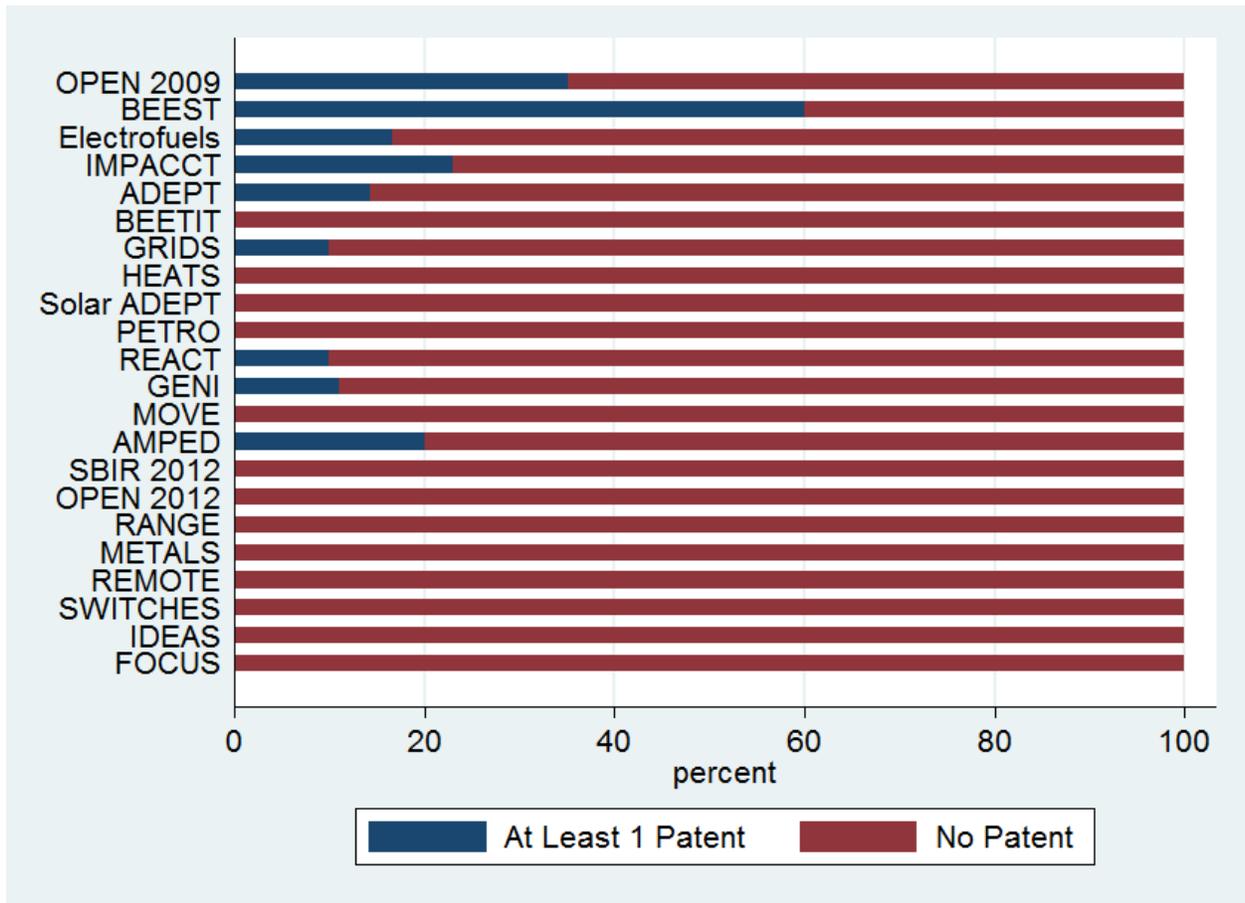


Figure 6 – Market Engagement by ARPA-E Programs

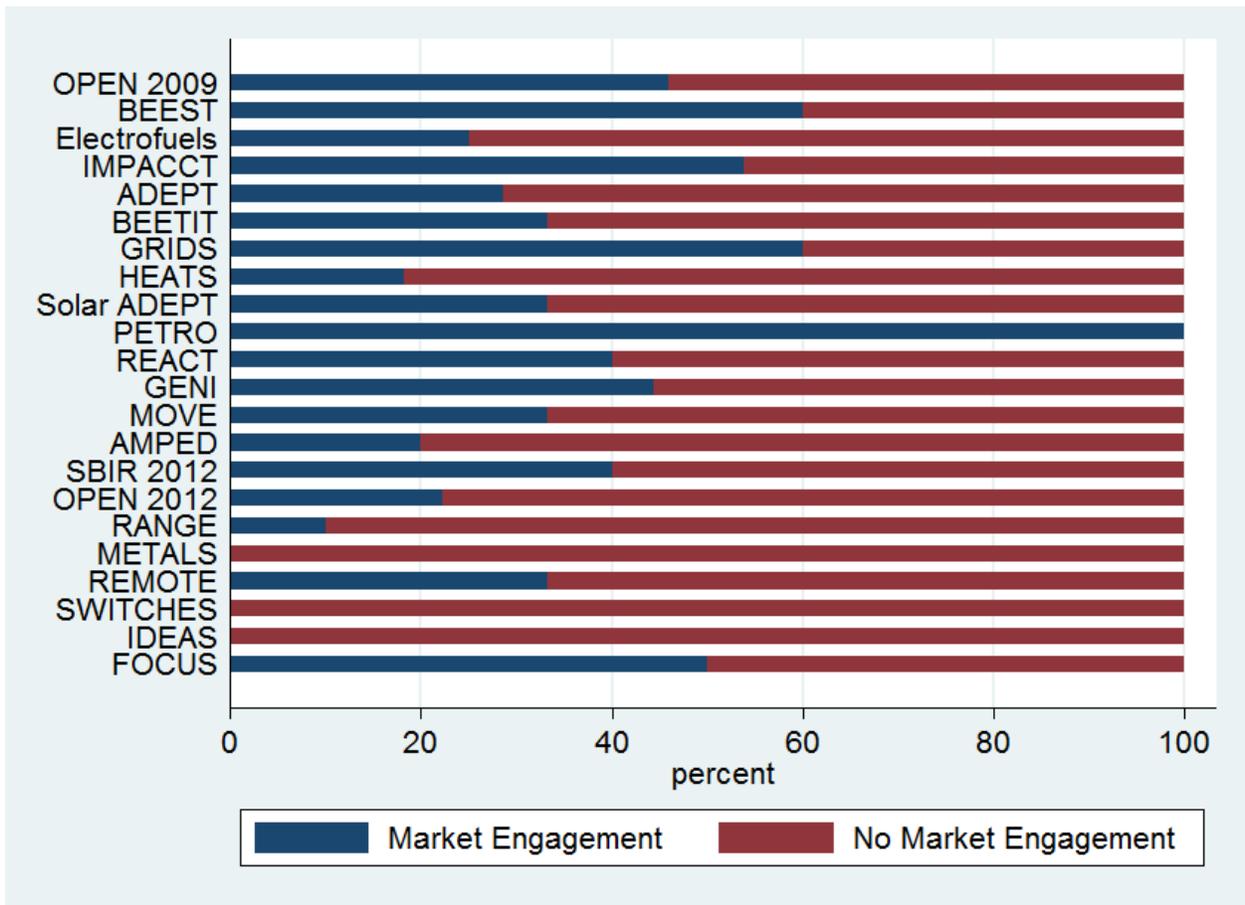


Figure 7 – Any Observable Output from ARPA-E Programs

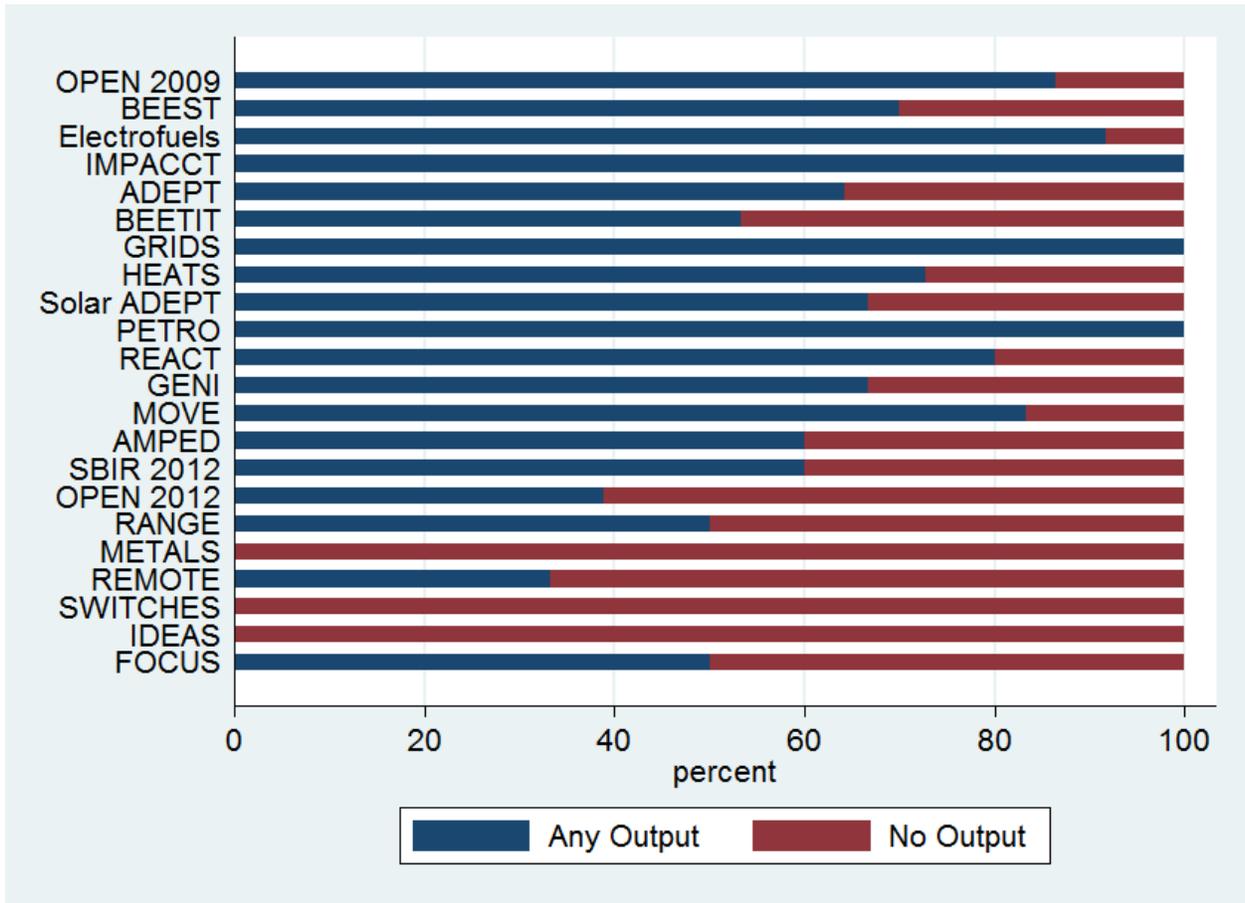


Table S1 – CFDA Codes for Energy R&D

| CFDA Number | CFDA Title | Awards Counted (Oct. 1, 2008 - Sep. 30, 2015) |
|-------------|---|---|
| 81.036 | INVENTIONS AND INNOVATIONS | 5 |
| 81.049 | OFFICE OF SCIENCE FINANCIAL ASSISTANCE PROGRAM | 3,211 |
| 81.057 | UNIVERSITY COAL RESEARCH | 20 |
| 81.086 | CONSERVATION RESEARCH AND DEVELOPMENT | 491 |
| 81.087 | RENEWABLE ENERGY RESEARCH AND DEVELOPMENT | 1,037 |
| 81.089 | FOSSIL ENERGY RESEARCH AND DEVELOPMENT | 250 |
| 81.121 | NUCLEAR ENERGY RESEARCH, DEVELOPMENT AND DEMONSTRATION | 169 |
| 81.122 | ELECTRICITY DELIVERY AND ENERGY RELIABILITY, RESEARCH, DEVELOPMENT | 356 |
| 81.129 | ENERGY EFFICIENCY AND RENEWABLE ENERGY TECHNOLOGY DEPLOYMENT, DEMONSTRATION AND COMMERCIALIZATION | 5 |
| 81.130 | CARBON CAPTURE AND STORAGE-FUTUREGEN 2.0 | 1 |
| 81.131 | EXPAND AND EXTEND CLEAN COAL POWER | 1 |
| 81.133 | GEOLOGIC SEQUESTRATION TRAINING AND RESEARCH GRANT PROGRAM | 49 |
| 81.134 | INDUSTRIAL CARBON CAPTURE AND STORAGE (CCS) APPLICATION | 38 |
| 81.135 | ADVANCED RESEARCH PROJECTS AGENCY - ENERGY | 263 |

Table S2 – Excluded CFDA Codes

| CFDA Number | CFDA Title | Awards Counted (Oct. 1, 2008 - Sep. 30, 2015) |
|-------------|--|---|
| 81.041 | STATE ENERGY PROGRAM | 87 |
| 81.042 | WEATHERIZATION ASSISTANCE FOR LOW-INCOME PERSONS | 160 |
| 81.079 | REGIONAL BIOMASS ENERGY PROGRAMS | 2 |
| 81.104 | OFFICE OF ENVIRONMENTAL CLEANUP AND ACCELERATION | 0 |
| 81.112 | STEWARDSHIP SCIENCE GRANT PROGRAM | 1 |
| 81.114 | UNIVERSITY REACTOR INFRASTRUCTURE AND EDUCATION SUPPORT | 1 |
| 81.117 | ENERGY EFFICIENCY AND RENEWABLE ENERGY INFORMATION DISSEMINATION, OUTREACH, TRAINING AND TECHNICAL ANALYSIS/ASSISTANCE | 126 |
| 81.119 | STATE ENERGY PROGRAM SPECIAL PROJECTS | 59 |
| 81.127 | ENERGY EFFICIENT APPLIANCE REBATE PROGRAM | 56 |
| 81.128 | ENERGY EFFICIENCY AND CONSERVATION BLOCK GRANT PROGRAM | 2,007 |
| 81.214 | ENVIRONMENTAL MONITORING/CLEANUP, CULTURAL AND RESOURCE MGMT., EMERGENCY RESPONSE RESEARCH, OUTREACH, TECHNICAL ANALYSIS | 0 |
| 81.502 | MISCELLANEOUS FEDERAL ASSISTANCE ACTIONS | 2 |
| 81.801 | STRATEGIC PETROLEUM RESERVE | 1 |
| 89.049 | -- | 1 |

Table S3 – Odds Ratio of Producing a Publication/Patent: Including Active Awards

| Model | 1 | 2 | 3 | 4 |
|------------------------------|------------------------|----------------------------|---------------------|----------------------------|
| Dependent Variable | At Least 1 Publication | | At Least 1 Patent | |
| Sample | ARPA-E & EERE | ARPA-E & Office of Science | ARPA-E & EERE | ARPA-E & Office of Science |
| Award Characteristics | | | | |
| ARPA-E | 1.910*** (0.293) | 0.948 (0.129) | 3.408*** (0.890) | 2.161** (0.678) |
| Ln(Project Duration) | 1.315* (0.193) | 1.419*** (0.128) | 0.557*** (0.116) | 0.377*** (0.073) |
| Ln(Net Obligation) | 1.411*** (0.074) | 1.589*** (0.064) | 1.705*** (0.138) | 3.287*** (0.418) |
| Start Year Fixed Effect | Y | Y | Y | Y |
| Org. Type Fixed Effect | Y | Y | Y | Y |
| Regression Statistics | | | | |
| Observations | 1935 | 5439 | 1672 | 4715 |
| Pseudo R^2 | 0.210 | 0.275 | 0.202 | 0.265 |

Sample: All ARPA-E, EERE, and Office of Science awards with R&D-related CFDA number

Exponentiated coefficients; Standard errors in parentheses

Logit with robust SE

Base org. type is Higher Ed

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table S4 – OLS Model for Producing a Publication/Patent: ARPA-E vs. EERE and Office of Science

| Model | 1 | 2 | 3 | 4 |
|------------------------------|------------------------|----------------------------|---------------------|----------------------------|
| Dependent Variable | At Least 1 Publication | | At Least 1 Patent | |
| Sample | ARPA-E & EERE | ARPA-E & Office of Science | ARPA-E & EERE | ARPA-E & Office of Science |
| Award Characteristics | | | | |
| ARPA-E | 0.221*** (0.031) | 0.012 (0.030) | 0.085*** (0.023) | 0.088*** (0.020) |
| Ln(Project Duration) | 0.033* (0.019) | 0.057*** (0.016) | -0.021** (0.010) | -0.009 (0.007) |
| Ln(Net Obligation) | 0.039*** (0.006) | 0.081*** (0.007) | 0.032*** (0.005) | 0.015*** (0.003) |
| Start Year Fixed Effect | Y | Y | Y | Y |
| Org. Type Fixed Effect | Y | Y | Y | Y |
| Regression Statistics | | | | |
| Observations | 1790 | 3481 | 1790 | 3481 |
| R^2 | 0.218 | 0.296 | 0.090 | 0.062 |

Sample: Completed ARPA-E, EERE, and Office of Science awards with R&D-related CFDA number

Standard errors in parentheses

OLS with robust SE

* p < 0.1, ** p < 0.05, *** p < 0.01

**Table S5 – Negative Binomial Model for Producing a Publication/Patent:
ARPA-E vs. EERE and Office of Science**

| Model | 1 | 2 | 3 | 4 |
|------------------------------|--------------------------|---------------------------------------|--------------------------|---------------------------------------|
| Dependent Variable | Publication Count | | Patent Count | |
| Sample | ARPA-E & EERE | ARPA-E & Office of Science | ARPA-E & EERE | ARPA-E & Office of Science |
| Award Characteristics | | | | |
| ARPA-E | 2.878*** (0.655) | 0.868 (0.163) | 2.638*** (0.721) | 1.910** (0.616) |
| Ln(Project Duration) | 1.094 (0.248) | 1.817*** (0.295) | 0.411*** (0.121) | 0.427*** (0.107) |
| Ln(Net Obligation) | 1.799*** (0.147) | 1.791*** (0.109) | 2.293*** (0.226) | 3.890*** (0.502) |
| Start Year Fixed Effect | Y | Y | Y | Y |
| Org. Type Fixed Effect | Y | Y | Y | Y |
| Regression Statistics | | | | |
| Observations | 1790 | 3481 | 1790 | 3481 |
| R^2 | 0.101 | 0.153 | 0.156 | 0.211 |

Sample: Completed ARPA-E, EERE, and Office of Science awards with R&D-related CFDA number

Exponentiated coefficients; Standard errors in parentheses

Negative binomial regression with robust SE

* p < 0.1, ** p < 0.05, *** p < 0.01

Table S6 – Odds Ratio of Producing a Publication/Patent: All DOE Offices

| Model | 1 | 2 |
|------------------------------|------------------------|---------------------|
| Dependent Variable | At Least 1 Publication | At Least 1 Patent |
| Award Characteristics | | |
| EERE | 0.279*** (0.046) | 0.289*** (0.074) |
| Office of Science | 0.728* (0.118) | 0.175*** (0.051) |
| FE | 0.563*** (0.107) | 0.203*** (0.079) |
| NE | 0.160*** (0.049) | -- |
| OE | 0.046*** (0.014) | 0.060*** (0.032) |
| Ln(Project Duration) | 1.850*** (0.161) | 0.750** (0.108) |
| Ln(Net Obligation) | 1.480*** (0.048) | 1.838*** (0.119) |
| Start Year Fixed Effect | Y | Y |
| Org. Type Fixed Effect | Y | Y |
| Regression Statistics | | |
| Observations | 5896 | 5644 |
| Pseudo R^2 | 0.262 | 0.198 |

Sample: Completed DOE awards with R&D-related CFDA number

Exponentiated coefficients; Standard errors in parentheses

Logit with robust SE

Base office is ARPA-E

* p < 0.1, ** p < 0.05, *** p < 0.01

Table S7 – OLS Model of Producing Outputs: ARPA-E Award Characteristics

| Model | 1 | 2 | 3 | 4 |
|------------------------------|------------------------|---------------------|---------------------|----------------------|
| Dependent Variable | At Least 1 Publication | At Least 1 Patent | Market Engagement | Any Output |
| Organization Type | | | | |
| Non-Profit | -0.414** (0.162) | 0.090 (0.119) | 0.110 (0.160) | -0.133 (0.159) |
| Established Company | -0.387*** (0.060) | 0.041 (0.039) | 0.058 (0.064) | -0.218*** (0.065) |
| Startup Company | -0.521*** (0.079) | 0.061 (0.102) | 0.421*** (0.087) | -0.072 (0.092) |
| Award Characteristics | | | | |
| Partnership | 0.177 (0.103) | 0.012 (0.047) | 0.069 (0.064) | 0.212*** (0.073) |
| Program Fixed Effect | Y | Y | Y | Y |
| Ln(Project Duration) | -0.013 (0.140) | -0.139* (0.069) | 0.276 (0.177) | 0.070 (0.111) |
| Ln(Net Obligation) | 0.067 (0.052) | 0.143*** (0.041) | 0.052 (0.052) | 0.077 (0.063) |
| Regression Statistics | | | | |
| Observations | 207 | 207 | 207 | 207 |
| R^2 | 0.363 | 0.291 | 0.279 | 0.357 |

Sample: Completed ARPA-E awards (minus national labs)

Standard errors in parentheses

OLS regression with robust SE clustered by program

Base org. type is Higher Ed.

* p < 0.1, ** p < 0.05, *** p < 0.01