Simultaneous Pursuit of Discovery and Invention in the US Department of Energy

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Abstract

There is a sharp boundary between basic and applied research in the organizational structure of the US Department of Energy (DOE). In this work, we consider a branch of DOE that was designed to operate across this boundary: the Advanced Research Projects Agency – Energy (ARPA-E). We hypothesize that much of energy research cannot be neatly categorized as basic or applied and is more productive outside of the confines of the basic/applied dichotomy; ARPA-E gives us an opportunity to test that hypothesis. We construct a novel dataset of nearly 4,000 extramural financial awards given by DOE in fiscal years 2010 through 2015, primarily to businesses and universities. We collect the early knowledge outputs of these awards from Web of Science and the United States Patent and Trademark Office. Compared to similar awards from other parts of DOE, ARPA-E awards are significantly more likely to jointly produce both a publication and a patent. ARPA-E has been highly productive in creating new technology, while also contributing new scientific knowledge. This observation points to the productive overlap of science and technology in energy research and, more generally, for mission-oriented research funding organizations.

Keywords: Research funding, basic research, applied research, discovery, invention, knowledge production

1. Introduction

There is a long-running debate over the role of government in funding applied research. There is a clear public need for advancement in technology areas such as energy and healthcare, and yet the use of public funds to influence private markets is controversial. One effect of this debate has been the sectioning off of basic and applied research funding streams, despite increasing awareness that the conceptual boundary between these two categories is artificial.

The US Department of Energy (DOE) in particular is organized around a sharp dividing line between basic and applied research, such that nearly all research funding programs are categorized as exclusively one or the other. In the past decade, however, DOE has undergone a number of changes, including the creation of an agency called Advanced Research Projects Agency – Energy (ARPA-E) to accelerate "transformational technological advances" in energy (110th Congress 2007). The creation of ARPA-E offers a rare opportunity to study the relationship between basic and applied energy research funding, as it appears to operate across the boundary between the two. In this paper, we compare ARPA-E projects to those funded by other parts of DOE, and we ask whether there is more or less knowledge produced from the union of science and technology at ARPA-E.

Many stories of major advances in technology provide qualitative evidence that basic and applied research efforts are complementary, with the discovery of new phenomena and the invention of new technology occurring hand-in-hand. Documented examples of breakthroughs from major industrial research centers of the past, such as Bell Labs, Xerox, and PARC, depict research that was driven simultaneously by curiosity and a desire to advance practical applications (Gertner 2012). Still, some questions remain: Does this synergy between basic and applied research also exist in the context of modern scientific research, which is conducted primarily with government funds at universities and government-owned laboratories? And does its effectiveness reach beyond isolated examples to improve the productivity of research funding institutions in aggregate?

These are interesting theoretical questions, as well as important questions of contemporary innovation policy. In the US, the existence of ARPA-E and mission-oriented research in general is threatened by the perception that government's proper role is only to fund basic research (Anadón, Gallagher, and Holdren 2017; Narayanamurti 2017). And as governments worldwide fulfill their Mission Innovation commitments and devote more public funds to energy innovation, it will be increasingly important to understand how research institutions can achieve transformative impact. Past and present institutional experiments must be evaluated in order to improve the effectiveness of future energy innovation spending (Chan et al. 2017).

We find that, in its first six years of operation, ARPA-E was highly effective in producing patents and publications. Projects funded by ARPA-E were significantly more likely to do research that was both published and patented than their counterparts elsewhere in DOE. From this, we infer that scientific discovery is not strictly the domain of basic research programs, and the isolation of basic research represents a missed opportunity for creating useful knowledge. If the intersection of basic and applied research increases the rate of knowledge production at DOE, this implies the need to reconsider the organizing principle for the department, which spends billions of dollars on R&D each year.[1]

In the next section, we review the division between basic and applied research at DOE and the role of ARPA-E. In Section 3, we describe our empirical approach of assessing research funded by different parts of DOE, and Section 4 provides the quantitative results of our analysis. The final sections of the paper discuss the implications of these results for R&D funding programs.

2. Background

2.1. The false dichotomy between basic and applied research

Vannevar Bush, in his famous report recommending the creation of the National Science Foundation, described two types of research: basic research, which "is performed without thought of practical ends," and applied research, which is the application of knowledge to practical purposes (Bush 1945). This vision of research as an activity that can be neatly categorized as either "basic" or "applied" in nature was highly influential. In the years since, however, many scholars of science and technology have found that is not useful to distinguish between "basic" and "applied" research on the basis of the researcher's intentions (Rosenberg 1990; Stokes 1997). Investigations that aim to serve a particular purpose may yield unexpected scientific discoveries, while researchers that aim to explore new phenomena often end up inventing new technology. There have been many instances of overlapping discovery and invention in the development of information technology (Narayanamurti, Odumosu, and Vinsel 2013) and other fields (Narayanamurti and Odumosu 2016).

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[1] In 2014, the federal budget for R&D at DOE was approximately $12 billion for Defense, Energy, and General Science (National Science Foundation and National Center for Science and Engineering Statistics 2015).

Some research funding agencies, especially those that serve an industry with a public customer such as space or defense, are organized to reflect the complementarity between curiosity-driven and application-driven research. Most notably, the Defense Advanced Research Projects Agency (DARPA) has contributed to many technological advances, using a “connected science model” to operate across the barrier between basic and applied research (Bonvillian 2009). Elsewhere in the Department of Defense (DOD), the entire spectrum of R&D activities is integrated within each of several organizations, including the Army, Navy, Air Force, and multiple defense agencies. Indeed, the Defense Science Board Task Force on Basic Research specifically recommended against centralizing basic research, stating that, “any potential savings, or other supposed benefits, that might accrue from such a restructuring would be far outweighed by distancing basic research from applied research and from the military operators” (Defense Science Board 2012). Even the NSF has recognized the value of connecting science and technology since at least 1983, with the creation of Engineering Research Centers (Bozeman and Boardman 2004), followed by Science and Technology Centers in 1987 and continuing in the past decade with the creation of the I-Corps program.

Meanwhile, in mission-oriented agencies such as DOE and the National Institutes of Health (NIH), the debate over public funding for applied research is more acute. Boundaries are often drawn to separate basic and applied research, perhaps due to the political tension surrounding transactions between government agencies and private firms. The appropriate balance between basic and applied research funding in the life sciences is a subject of frequent debate (Collins 2012; Comroe and Dripps 1976; Moses et al. 2005), although a recent study found no substantial difference in commercial patenting as a function of “basicness” for NIH grants (Li, Azoulay, and Sampat 2017).

Many observers have recognized the particularly sharp boundary between basic and applied research at DOE (American Academy of Arts & Sciences 2013; Anadón et al. 2016; The National Academies 2007). Research expenditures in DOE are divided among the Office of Science and four technology offices such as the Office of Energy Efficiency and Renewable Energy (EERE). While the technology offices fund “applied research, development, demonstration and deployment activities” (U.S. Department of Energy 2016), the Office of Science identifies strongly as a basic research agency. A report published in 2014 by Basic Energy Sciences within Office of Science depicts a clear boundary between basic research and all other department activities (Figure A1), even listing distinct goals and metrics.

In response to growing concern over the effectiveness of DOE’s research funding, Secretaries of Energy Chu and Moniz oversaw several important changes to the department. In 2010, DOE established several Energy Innovation Hubs, which are “integrated research centers that combine basic and applied research with engineering to accelerate scientific discovery that addresses critical energy issues" (Anadón 2012; U.S. Department of Energy n.d.). Several cross-cutting initiatives were created to combine expertise across the department in areas such as grid modernization and the energy-water nexus. In 2014, the DOE leadership structure was reformed to allow a single administrator (the Under Secretary of Science and Energy) to head up the Office of Science as well as the technology offices (Malakoff 2014), although this change has since been reversed under Secretary of Energy Perry.

2.2. The role of ARPA-E

Another major change at DOE was the creation of ARPA-E in 2009; this new agency was intended "to overcome the long-term and high-risk technological barriers in the development of energy technologies" (110th Congress 2007). Inspired in part by DARPA, ARPA-E was designed to accelerate transformational advances in energy technology (The National Academies 2007). Rather than being embedded within either Office of Science or any of the technology offices, the Director of ARPA-E has greater flexibility by reporting directly to the Secretary of Energy. Because it exists outside the conventional departmental structure (Figure 1), research funded by ARPA-E is not implicitly defined as either basic or applied.

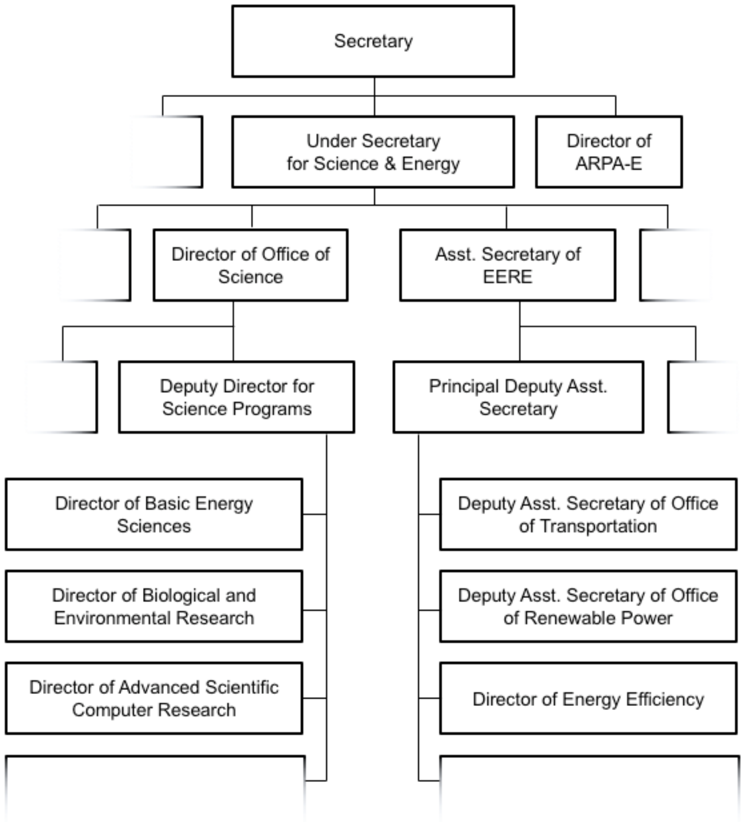

Figure 1. An illustrative portion of the organizational chart for the US Department of Energy, as of 2016

Public documentation of ARPA-E's purpose often describes the agency as distinct from either exclusively basic or applied research. ARPA-E's authorizing legislation charged the agency with "identifying and promoting revolutionary advances in *fundamental* and *applied* sciences" (emphasis added) (110th Congress 2007; 111th Congress 2011). In its first annual report, ARPA-E was described this way: "By bringing together experts from all walks of science, technology, and business, ARPA-E breaks down silos between disciplines. This cross-disciplinary inquiry is essential to bridge the gap between basic and applied research and development." More recently, DOE's 2017 budget request described ARPA-E as "complementing and expanding the impact of DOE's basic science and applied energy programs" (U.S. Department of Energy 2016).

In terms of Technology Readiness Level (TRL), ARPA-E has defined its purview as relatively early-stage technology research.[2] And in its solicitations for proposals, ARPA-E positions itself between the

[2] The TRL scale was developed by NASA and adopted by the Department of Defense to assess technology maturity

basic and applied research funding streams at DOE, issuing the following instructions for applicants to determine whether a 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)

Elsewhere in its solicitations, the agency has described its domain as "applied research and development of new technologies." However, the use of "applied" in this context serves to set ARPA-E apart from basic research, while the emphasis on "new technologies" distinguishes it from the applied research investments in the technology offices, which are organized around established technology areas. The assessment of ARPA-E by a committee of the National Academies[3] notes a similar distinction, saying, "The applied offices [of DOE] make their applied research investments hew closely to technology roadmaps that appear less risky, with the expectation of continuing their investments in particular technologies or programs over long periods of time..." (National Academies of Sciences Engineering and Medicine 2017).

Based on the sum of evidence from public documentation, the aim of ARPA-E appears to be funding projects that are too technology-focused to be funded as basic research but are too novel to be funded as applied research. An example ARPA-E project illustrates this concept.

In 2012, ARPA-E awarded $4.3 million to a team led by Michael Aziz, Professor in the School of Engineering and Applied Sciences at Harvard University. The goal of the project was to develop an organic aqueous flow battery, which would be highly desirable as a low-cost energy storage method to help accommodate intermittent renewable sources of electricity on the grid. By gaining a deeper

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with levels 1 through 9 (U.S. Department of Energy, 2011). In its first annual report, ARPA-E stated, "Most ARPA-E funded projects range from technology concept (TRL 2) through component validation in laboratory experiment (TRL 4) … The TRL space between TRL 2 and TRL 4 is known as a 'valley of death' for technology development" (ARPA-E 2010). Then in 2011, ARPA-E solicitations stated, "ARPA-E operates mainly within the 'valley of death' between TRL-3 and TRL-7" (ARPA-E 2011). The agency has not used technology readiness level (TRL) to describe its projects since 2012.

[3] Our analyses here originated as a working paper submitted to this committee .

understanding of the chemical reactions involved, Aziz's group was able to create a proof-of concept device. The researchers published a number of journal articles, including in *Nature* and *Science* (Huskinson et al. 2014; Lin et al. 2015); they also filed two patent applications and began partnering with a company to commercialize the technology (ARPA-E 2016).

Other ARPA-E projects have been similarly aimed at creating impactful new technologies. A team led by Hong-Cai Zhou, Professor of Chemistry at Texas A&M, created new porous materials with promising properties for carbon capture and storage. Researchers at Palo Alto Research Center created a way to optically sense the state of charge and health for electric vehicle (EV) batteries. A team at Arkansas Power Electronics International created a silicon carbide transistor for fast and efficient EV charging modules, leading to the company's acquisition by Cree in 2015. Each of these teams published their research in the open literature and also were issued patents protecting their intellectual property.

2.3. A productive intersection between science and technology

Is the research into organic aqueous flow batteries applied, because it advanced the frontier of battery technology? Or is the research basic, because it advanced our understanding of electrochemistry? This project cannot be neatly classified as either basic or applied, and furthermore, it seems as though attempts to separate the two would have hindered progress on both fronts. The focus on technology guided the team's scientific inquiry, and the scientific discovery facilitated the invention. We hypothesize that much of energy research is positioned at the intersection of science and technology, and that these efforts can be productively funded outside of the basic/applied dichotomy.

To test this hypothesis, we measure the proportion of awards that published or patented, and we also look for awards in which results were both published and patented. In doing so, we build on the idea that papers and patents represent the preferred disclosure methods of open science and commercial science, respectively (Dasgupta and David 1994). These categories of knowledge production are not mutually exclusive, as evidenced by patent-paper pairs that embody the same piece of knowledge (Fehder, Murray, and Stern 2014; Gans, Murray, and Stern 2013; Murray 2002; Murray and Stern 2007). In this paper, we extend this idea to the level of the research project and ask whether a given project, which was supported by one funding source and conducted by the same team of researchers, produces both a patent and a publication. We take the joint output of these disclosures to indicate a higher likelihood that the project cannot be categorized as either basic or applied, and we also use the rates of publishing and patenting as relative indicators of research productivity overall.

There are limitations to using publications and patents to measure research progress. First, these metrics may overstate the value of some projects in a funding program's portfolio. The barrier for producing a publication is relatively low, and academic awardees in particular are incentivized to publish results regardless of quality. The fact that an awardee published an article does not indicate that a significant discovery was made. Similarly, every patent does not represent a useful invention. Patent applications are often reviewed with low or inconsistently applied standards (Rassenfosse, Jaffe, and Webster 2016), and issued patents have a low probability of ever being licensed or litigated (Lemley and Shapiro 2005).

Second, it is clear that patents and publications, while being common and convenient metrics of productivity, do not capture the full value of research support from public agencies. Research contributes to tacit knowledge that accumulates within the research team and transfers without ever being formally disclosed. Inventions resulting from funded research may be held as trade secrets rather than being disclosed. And while knowledge production is a valuable goal, it is not the only beneficial outcome of research funding. Award funds may be used to support graduate student and postdoctoral training, which amounts to an investment in future knowledge production as those researchers advance in their own careers.

3. Methods

In order to examine ARPA-E's melding of basic and applied research, we compare ARPA-E to parts of DOE that approach these two categories separately: Office of Science as a funder of basic research, and EERE as the applied technology office with the greatest subject matter overlap with ARPA-E. We isolate a subset of projects from these offices that are superficially similar to ARPA-E awards, while noting that these projects do not reflect the full scope of work done by Office of Science and EERE. The Office of Science is a steward of 10 of the 17 DOE national laboratories (U.S. Department of Energy, 2016), the activities of which are not included in our analysis, while EERE stewards the National Renewable Energy Laboratory and funds a wide range of technology demonstration and deployment projects.

An overview of our methods follow, with more details included in the Appendix. We use transaction data for prime recipients of grants or "other financial assistance" from USAspending.gov for the fiscal years (FY) 2009-2015 and combine these transactions to arrive at a dataset of financial awards given by DOE. We do not consider funding that is distributed via contracts. This exclusion is important to note, because contracts are the primary mechanism for funding research at the national labs.[4] ARPA-E uses cooperative agreements, which differ from grants in that they entail "substantial involvement" between the agency and the recipient, as its primary mechanism of distributing funds. We choose grants and cooperative agreements (referred to collectively in this paper as "awards") as the most relevant basis for comparison to ARPA-E.

Starting with the awards given by ARPA-E, EERE, and Office of Science, we take the following steps limit our dataset to awards that we consider comparable with ARPA-E on observable characteristics:

- **Exclude awards with program titles that are obviously unrelated to R&D.** In the data provided by USAspending.gov, awards are categorized by a program title based on the Catalog of Federal Domestic Assistance (CFDA). These titles are quite broad and do not allow fine segmentation of specific activities. The CFDA numbers considered here to be within the scope of energy R&D, as well as those that were excluded, are listed in Table A1 and Table A2 in the Appendix.
- **Exclude awards that began before FY 2010 or ended after FY 2015.** The first ARPA-E funds were awarded in FY 2010, so this marks the beginning of the study period.
- **Exclude awards that are funded at a lower level than the smallest ARPA-E award or at a higher level than the largest ARPA-E award.** The remaining range of award size is $5,000 to $10.2 million. Many EERE awards were excluded in this step, with obligation amounts of up to several hundred million USD. This exclusion ensures common support for comparisons that account for funding level.
- **Exclude awards that are to performers labeled as "Government" or "Other".** The remaining organization types are Higher Education, For-Profit, and Non-Profit.

Following the exclusions above, the primary dataset used in this work contains 3,775 awards (256 from ARPA-E, 1,196 from EERE, and 2,323 from Office of Science) and accounts for over $3 billion in financial assistance.[5]

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[4] 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).

[5] Almost all of the Office of Science awards to For-Profit awardees come from the DOE SBIR/STTR program. Many of these awards represent research efforts funded separately by the technology offices, yet they are administered by Office of Science, so they appear as Office of Science awards in our data.

For this set of awards, we collect data on the publishing and patenting activity directly attributable to each award. Publication outputs are downloaded from the Web of Science (WOS), a subscription-based product from Thomson Reuters, and patent outputs were downloaded from the US Patent and Trademark Office (USPTO). These outputs are observed through the end of FY 2016, 7 years after the start of the earliest award that we observe and 1.5 years after the start of the latest award. Only those outputs which listed a specific award number are captured; our counts do not include publications that acknowledge DOE support generically (e.g. "an award from ARPA-E"). We observe 351 patents and 5,181 publications acknowledging an award in our dataset; patent types and publication categories are shown in the Appendix in Figure A2 and Figure A3.

We measure the relative value of the patents produced by each award by noting which patents in our dataset have been cited by at least one other patent through the end of FY 2016. Citation-weighted patent counts are more reliable measures of value than simple patent counts (Trajtenberg 1990), and yet there are relatively few patents in our dataset that have been cited in this short observation period. For publications, we measure impact using citation percentiles for a given field and year, to account for time lag and idiosyncratic differences between fields (Bornmann and Marx 2012). The thresholds for "highly cited papers" (within the first percentile by field and year) are obtained from WOS. We also measure whether the article appeared in a "top journal", defined as one of the 40 journals with the greatest number of "highly cited" papers published from 2006-2015.

4. Results

Across our dataset of DOE awards, ARPA-E has greater output per award with respect to each of the variables that we tested, compared to the sets of awards from EERE and Office of Science (Table 1). For example, 20% of ARPA-E awards produced a patent in our observation period, and nearly half of ARPA-E awards (48%) produced a publication. By performing a t-test allowing for unequal variance, we establish that the difference in means between ARPA-E and the other offices are greater on nearly all outputs with 99% confidence ($t > 2.6$, results not shown).

Table 1: Summary Statistics for DOE Awards Dataset

Variable	ARPA-E N = 256	EERE N = 1,196	Office of Science N = 2,323		
		Mean		Min.	Max.
Net obligation (mil. USD)	2.36	1.36	0.43	0.005	10.2
Project duration (years)	2.46	2.62	1.96	0.1	5.7
Number of patents	0.52	0.15	0.02	0	30
Number of publications	2.42	1.01	1.55	0	63

	Percent				
At least 1 patent and at least 1 publication[a]	11%	3%	1%	0	1
At least 1 output (either patent or publication)	57%	24%	28%	0	1
At least 1 patent	20%	6%	1%	0	1
Emerging Cross-Sectional Technologies	13%	4%	0%	0	1
Chemistry and Metallurgy	8%	2%	1%	0	1
Electricity	12%	3%	1%	0	1
Operations and Transport	7%	2%	1%	0	1
At least 1 cited patent	6%	2%	0%	0	1
At least 1 publication	48%	21%	27%	0	1
Energy & Fuels journal	16%	10%	2%	0	1
Physics	14%	4%	10%	0	1
Chemistry	23%	5%	7%	0	1
Materials Science	13%	6%	3%	0	1
Engineering	16%	12%	3%	0	1
At least 1 highly cited publication[b]	13%	4%	6%	0	1
At least 1 top journal publication[c]	18%	4%	8%	0	1

[a] Outputs measured are those patents and articles that cited the award number and were published/issued before Oct. 1, 2016

[b] "Highly cited" means that the article received a citation count in the top 1% for the subject category in the year of publication

[c] "Top journal" means that the journal is ranked in the top 40 by number of highly cited papers from 2006-2016

However, even within the restrictions imposed on the dataset, the awards given by ARPA-E are dissimilar in many ways from those given by both EERE and Office of Science, such as the size of the award. Among the awards we measure, the ARPA-E awards are on average larger than either the Office of Science awards or the EERE awards. We test whether the amount of money devoted to a project impacts its ability to yield papers and patents, and we find a positive correlation between funding amount and probability of jointly publishing and patenting (Table A4 in the Appendix).

Other aspects of the awards in our dataset could also impact their productivity, such as the time elapsed since the award was given. It often takes years to observe papers and patents after a project ends (see Figure A4 for an illustration), so the awards that occur later in the observation period have fewer measurable outputs. There may also be time-variant factors that affect the output of the entire research community in a given year. Finally, the institutional environment of the research team is also expected to impact the rate of producing each of the measured outputs.

Using control variables to account for the factors above, we model the probability of binary output variables using both logistic regression (Equation 1) and linear regression. Y_{ijk} is the outcome of award i; X_i is the sponsoring organization (ARPA-E, EERE, or Office of Science); φ_j is a fixed effect for the organization type; γ_k is a fixed effect for the fiscal year when the award began.

$$(1) \qquad logit\left(P\left(Y_{ijk}\right)\right) = \beta_0 + \beta_1 X_i + \beta_2 \ln(funding\ amount_i) + \varphi_j + \gamma_k$$

The quantities listed in the tables below are the exponentiated coefficients from logit regression, i.e. the odds ratio for achieving a given outcome. For count variables, we model the probable value using negative binomial regression, in which case the exponentiated coefficient is the incidence rate ratio for two groups of awards.

In the Appendix, we perform a number of robustness checks. To fully ensure that we have accounted for the positive correlation of funding amount and probability of outcomes, we repeat the following analyses using coarsened exact matching to reduce imbalance in funding amount across the three groups (Table A5 and Table A6). We also repeat the analyses with a stricter definition of R&D awards beyond CFDA codes; in Table A7, we exclude 525 awards that are considered not R&D internally by EERE[6] as well as 208 awards that have the words "workshop" or "conference" in the project description. Finally, we test the effect of including awards that were still active as of Oct. 1, 2015, including many Office of Science awards, which are often renewed at the end of a funding cycle if they are judged successful (Table A8).

4.1. Joint output of patents and publications

Our first goal is to identify the number of awards that produce jointly at least one publication and at least one patent, and to compare the frequency of this outcome across the three DOE research sponsors. Over the entire dataset of DOE awards, the joint observation of publication and patents is rare, occurring in only 70 of 3,775 (1%) of awards. However, the proportion does vary by office: 11% of ARPA-E awards, compared to 1% of Office of Science awards and 3% of EERE awards.

We note that our measurements of publication and patenting activity do not capture the full extent of knowledge produced by the research investments in our dataset. Many of these awards, particularly those in more recent years, likely had pending patent applications and publications under review at the end of the observation period, so the proportion of awards achieving a given output is underestimated; this effect is illustrated in the Appendix in Figure A4.

Regression analysis confirms that ARPA-E has a broad positive advantage on the joint output of publications and patents (Table 2) over several specifications, including a fixed effect for the type of recipient and an interaction effect of recipient type and sponsoring offices. The odds ratios of a joint output from the set of EERE and Office of Science awards that we consider is significantly less than 1,

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[6] Per communication with EERE's Project Management Coordination Office.

compared to ARPA-E. The OLS result (Model 4) is ~10% lower probability of a joint output for those offices, matching the sign and significance of the logit results.

Table 2: Joint Outputs from DOE Awards Dataset

Dependent Variable: At least 1 patent and at least 1 publication	(1)	(2)	(3)	(4)
Model:	Logit	Logit	Logit	Linear
EERE	0.162***	0.284***	0.184***	-0.101***
	(0.049)	(0.086)	(0.090)	(0.034)
Office of Science	0.036***	0.127***	0.127***	-0.106***
	(0.014)	(0.056)	(0.067)	(0.033)
Ln(Net Obligation)		2.077***	2.058***	0.008***
		(0.287)	(0.290)	(0.002)
For-Profit	0.878	0.744	0.560	-0.031
	(0.223)	(0.195)	(0.241)	(0.041)
Non-Profit	0.333**	0.429	0.327	-0.074
	(0.178)	(0.233)	(0.371)	(0.061)
EERE · For-Profit			2.012	0.037
			(1.219)	(0.043)
EERE · Non-Profit			2.064	0.067
			(2.726)	(0.062)
Office of Science · For-Profit			0.912	0.027
			(0.689)	(0.041)
Office of Science · Non-Profit			--	0.083
				(0.061)
Fiscal Year F.E.	Y	Y	Y	Y
N	3432	3432	3197	3775
(Pseudo) R^2	0.157	0.202	0.195	0.049

Notes: Robust standard errors in parentheses. Logit results are exponentiated coefficients (odds ratios). Base office is ARPA-E and base org. type is Higher Ed.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

We measure the production of high impact papers as well, and we find that the probability of producing both a patent and a high impact paper is also higher for ARPA-E (Table A9 in the Appendix). Knowing that ARPA-E awards have higher odds of a joint paper/publication output compared to EERE and Office of Science awards, however, does not tell a complete story. Next, we investigate whether this increase is due to higher rates of patenting, publishing, or both.

4.2. Patents

ARPA-E awards are significantly more likely to generate a patent compared to similar awards from EERE and Office of Science, as shown in Table 3. Unsurprisingly, awards to companies have an advantage in patenting over academic awardees. Both the number of patents per award and the odds of patenting at all are significantly lower for the awards from both EERE and Office of Science compared to

ARPA-E. The effect is less significant when we measure cited patents specifically (Model 3), perhaps because cited patents are a relatively rare outcome, obtained by only 1% of all awards in the dataset.

Table 3: Patent Outputs from DOE Awards Dataset

Dependent Variable:	Number of patents	At least 1 patent	At least 1 cited patent
	(1)	(2)	(3)
Model:	Neg. Binomial	Logit	Logit
EERE	0.268***	0.191***	0.437
	(0.113)	(0.085)	(0.399)
Office of Science	0.173***	0.129***	0.126*
	(0.083)	(0.062)	(0.158)
Ln(Net Obligation)	2.156***	1.943***	2.090***
	(0.244)	(0.175)	(0.369)
For-Profit	2.489***	1.965*	4.862**
	(0.779)	(0.704)	(3.708)
Non-Profit	2.681*	1.721	0.761
	(1.605)	(1.199)	(0.880)
EERE · For-Profit	2.574*	1.912	0.735
	(1.257)	(0.953)	(0.726)
EERE · Non-Profit	0.274	0.475	--
	(0.222)	(0.434)	
Office of Science · For-Profit	1.107	1.457	0.419
	(0.577)	(0.782)	(0.613)
Office of Science · Non-Profit	0.000***	--	--
	(0.000)		
Fiscal Year F.E.	Y	Y	Y
N	3775	3491	3429
Pseudo R^2	0.180	0.223	0.254

Notes: Robust standard errors in parentheses. Results are exponentiated coefficients (odds ratios). Base office is ARPA-E and base org. type is Higher Ed.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

We also ask whether each award produced patents in specific categories under the Cooperative Patent Classification system. Of particular interest are patents labeled "Emerging Cross-Sectional Technologies," most of which are classified as "Technologies or Applications for Mitigation or Adaptation Against Climate Change." Odds of patenting in this category and several others are reduced for EERE and Office of Science awards compared to ARPA-E; full results breaking down the likelihood of different patent types are shown in the Appendix (Table A10).

4.3. Publications

Next we consider the publication-related outputs from each award in the dataset. Here, the comparison of ARPA-E with EERE is quite different from the comparison with Office of Science (Table 4). EERE awards are significantly less likely to produce a publication than ARPA-E awards (Model 2). Office of Science awards, on the other hand, have roughly the same odds of publishing as similar ARPA-

E awards, for both For-Profit awardees (most of which are actually DOE-wide SBIR awardees) and academic awardees.

Table 4: Publication Outputs from DOE Awards Dataset

Dependent Variable:	Number of publications	At least 1 publication	At least 1 highly cited publication	At least 1 top journal publication
	(1)	(2)	(3)	(4)
Model:	Neg. Binomial	Logit	Logit	Logit
EERE	0.670*	0.339***	0.814	0.451**
	(0.156)	(0.093)	(0.271)	(0.140)
Office of Science	2.003***	1.006	1.817*	1.887**
	(0.434)	(0.268)	(0.590)	(0.532)
Ln(Net Obligation)	2.040***	1.946***	2.076***	1.965***
	(0.111)	(0.075)	(0.157)	(0.132)
For-Profit	0.145***	0.103***	0.358**	0.236***
	(0.040)	(0.033)	(0.146)	(0.093)
Non-Profit	1.156	0.556	0.927	2.406
	(0.607)	(0.316)	(0.666)	(1.353)
EERE · For-Profit	0.839	1.327	0.123***	0.441
	(0.300)	(0.488)	(0.082)	(0.245)
EERE · Non-Profit	0.087***	0.225**	0.100**	0.109***
	(0.053)	(0.142)	(0.102)	(0.080)
Office of Science · For-Profit	0.427***	1.060	0.133***	0.185***
	(0.135)	(0.366)	(0.076)	(0.094)
Office of Science · Non-Profit	0.228***	0.524	0.760	0.188***
	(0.129)	(0.315)	(0.600)	(0.119)
Fiscal Year F.E.	Y	Y	Y	Y
N	3775	3775	3775	3775
Pseudo R^2	0.121	0.259	0.219	0.235

Notes: Robust standard errors in parentheses. Results are exponentiated (odds ratios). Base office is ARPA-E and base org. type is Higher Ed.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

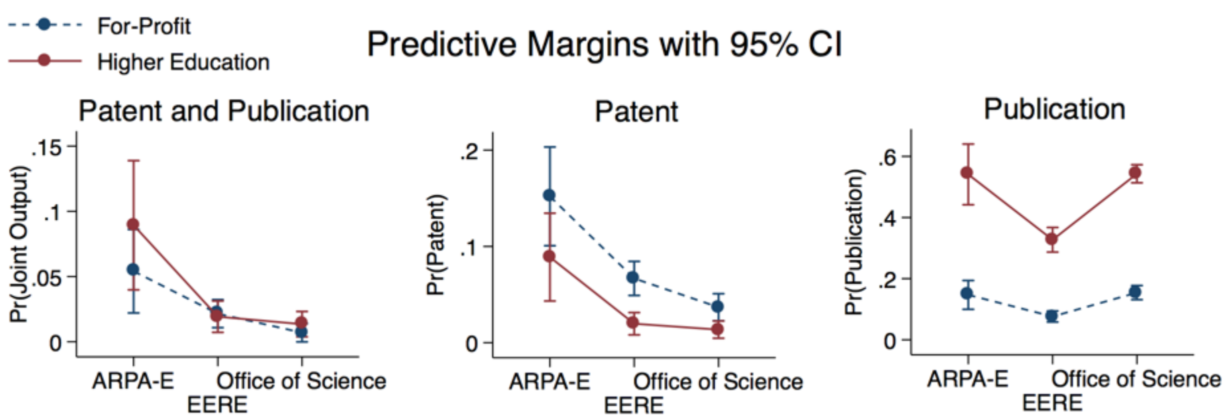
On the measures of high quality publications (Models 3 and 4), we see significant interactions between organization type and sponsoring office. For both "highly cited" and "top journal" publications, there are greater odds for Office of Science academic awards over ARPA-E academic awards. Yet we find lower odds of high impact papers for Office of Science for-profit awards over ARPA-E for-profit awards.[7]

[7] Using an exponentiated coefficient, the interaction effect in a logit regression can be interpreted as a ratio of odds ratios. For example, the odds ratio of a highly cited paper for Office of Science over ARPA-E, specifically for For-Profit awardees, is 0.241; this value is obtained by multiplying the "Office of Science · For-Profit" interaction term (0.133 in Model 3) by the "Office of Science" odds ratio (1.817 in Model 3).

We also measure the odds of producing different types of papers based on the subject of the journal. ARPA-E has an advantage in publishing over Office of Science in each subject category measured except for Physics. Full results on the likelihood of producing different publication types are shown in the Appendix (Table A11).

Figure 2 summarizes all of the above results by plotting the predictive margins of various outputs for For-Profit and Higher Ed. awards across the three offices.

Figure 2: Probability of Outputs Across Sponsoring Offices and Organization Types



Note: Non-Profit awards are not plotted for clarity. Plots were generated by the *margins* and *marginsplot* commands in Stata (Williams 2012). Regression data for these plots are found in (a) Table 2, Model 3; (b) Table 3, Model 2; and (c) Table 4, Model 2.

5. Discussion

The results above can be summarized as three key findings: (1) ARPA-E has funded a relatively high proportion of awards that resulted in both a published article and an issued patent. This trend holds even when only high impact papers are considered. (2) ARPA-E awards are more likely to produce IP compared to their counterparts elsewhere in DOE. (3) ARPA-E awards have a high likelihood of publishing, on par with similar Office of Science awards.

Our findings confirm the self-stated positioning of ARPA-E as neither exclusively basic nor applied research, and they support our hypothesis that allowing these two domains to intersect can lead to greater research productivity overall. If scientific and technological knowledge pursuits were truly separate activities, one would expect a tradeoff between rates of patenting and publishing. Instead, ARPA-E awardees have excelled at patenting while matching or exceeding expectations in publishing. The high rate of patenting from ARPA-E aligns well with the agency's focus on new technology, and yet the rate of publishing is comparable to DOE's basic research office.

ARPA-E was intended to have long-term transformative impact on energy technology, and the organization was designed with several features in service of this goal:

1. *Different proposals.* The pool of ideas submitted to ARPA-E may differ from those submitted to other DOE funding streams, due to their specific request for early-stage technology ideas. This may influence the composition of the applicant pool (e.g. more commercially active academic labs) and/or the ideas those applicants propose (e.g. ideas perceived as too basic or too applied for other programs).
2. *Different selection criteria.* Rather than adhering strictly to peer review scores as selection criteria, ARPA-E's program directors have significant latitude to select proposals that have potential for impact (National Academies of Sciences Engineering and Medicine 2017). They may use their discretion to fund projects that would be considered too basic for the applied offices and yet too applied for Office of Science.
3. *Different incentives for awardees*. The disclosure decisions of awardees may depend on the priorities of the program directors, e.g. program directors encouraging patent applications. The preferences of program directors at ARPA-E may be especially influential because they have the ability to terminate a project they deem unsuccessful.

While we are not able to attribute our findings to any one policy or practice, we surmise that these features have allowed ARPA-E to generate more knowledge outputs across the boundary between science and technology, compared to its counterparts in DOE that focus on only one side of the divide. This suggests that ARPA-E, which the Trump administration has proposed eliminating, should continue to be funded. ARPA-E's work at the intersection of discovery and invention supports DOE's mission to address energy challenges "through transformative science and technology solutions" (U.S. Department of Energy 2018).

Our results also imply steps that should be taken to enhance the productivity of DOE's other research funding organizations. The openness to new ideas that could result in discoveries, inventions, or both should not be limited to ARPA-E. Given the small size of ARPA-E, there may yet be a large pool of untapped ideas that combine elements of basic and applied research in energy. The Office of Science could support more downstream innovation and have a greater impact by expanding their scope to include research that is relevant to technology. Conversely, the so-called applied offices could have greater impact upstream by being open to research that advances science. The stakes of this missed opportunity in

Office of Science are particularly high, as it is a dominant force in physical science funding in the US, and yet it has been criticized for discouraging invention or technology creation (American Academy of Arts & Sciences 2013).

DOE funds many different types of research activities, not all of which lie at the interface of science and technology. Some efforts are geared to produce discoveries, such as the High Energy Physics program in Office of Science, which funds work on particle accelerators. Other programs in the technology offices are intended to make progress along certain technological paths, such as the SunShot Initiative in EERE, which aims to reduce the cost of solar energy. Nonetheless, a large part of DOE's work is advanced materials research (for energy storage, light absorption, carbon capture, etc.), which is centrally positioned between science and engineering and likely to benefit from a closer interaction between the two.

In order for DOE to fulfill its energy mission, it must fund research in a way that allows science and technology to coexist with minimal friction between them. We note, however, that a porous boundary between basic and applied research does not require the same close linkage between research and development, which is the improvement of specific products. Programs in development, demonstration, and deployment, which comprise a large portion of EERE and the other technology offices, may benefit from being managed separately from exploratory research efforts.

6. Conclusion

The disclosure of new knowledge indicates progress toward impact for public research funding agencies, whether that impact is advancing the frontier of science, or the frontier of technology, or both. By measuring the joint output of papers and patents, we empirically identify ARPA-E as an example of the productive union of these two frontiers.

The evidence suggests that the agency's strategic focus on practical advances in technology has not prevented their awardees from advancing science as well. Instead, ARPA-E has succeeded in simultaneously promoting discovery and invention, indicating that these can be complementary activities. Research efforts that are not aimed solely at either discoveries or inventions may be overlooked by funders that identify themselves as exclusively either basic or applied research. Our findings imply that the use of these two categories as an organizing principle for research funding agencies is a missed opportunity for impact.

Future research in this area could investigate other metrics of productivity for ARPA-E research funding beyond direct acknowledgement in papers and patents. A case study approach will be useful for documenting other outcomes, such as technology transfer, startup formation and growth, and market deployment. As projects continue to develop after ARPA-E involvement, outcomes become paradoxically both harder to measure and more relevant to the ultimate aim of the agency: transformative impact on the marketplace for energy technology.

Acknowledgements

This work was supported in part by a grant from BP to the Environment and Natural Resources Program and the Science, Technology, and Public Policy Program at the Belfer Center for Science and International Affairs. A. P. G. was also supported by a consulting engagement with the National Academies of Science, Engineering and Medicine for a study on ARPA-E. We thank anonymous reviewers for their comments and suggestions, and we are grateful for helpful discussions with Laura Diaz Anadon, Paul Beaton, Gail Cohen, Kevin Doran, Michael Kearney, Scott Stern, and Jeff Tsao. All errors or omissions are our own.

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Appendix

1. Additional Methods

We filter the USAspending.gov data to include only awards from certain offices in DOE. Award numbers begin with the prefix "DE", followed by a two letter code indicating the office or program where the award originated. The codes of interest are: AR = ARPA-E, SC = Office of Science, EE = Energy Efficiency and Renewable Energy. We then remove duplicate transactions with the same award number and same funding amount in the same fiscal year.

We check the quality of our processed data by comparing to alternative data sources on a subset of awards, obtained from the ARPA-E (https://arpa-e.energy.gov/) and Office of Science (https://pamspublic.science.energy.gov) websites. The mean value of measurement error for the total funding amount per award is -2.7% for ARPA-E awards, where 85% of values are between -5.0% and 0.0% error. For Office of Science awards, the mean measurement error for funding amount is -0.7%, and 95% of values are between -5.0% and 0.0% error.

We also use the data from the ARPA-E and Office of Science websites to identify the name of the program that funded each award. Approximately 30% of ARPA-E awards are from an open solicitation, covering all types of energy technology, and the rest are targeted programs, designed around a specific unaddressed technological problem in the energy space. Awards from 22 different ARPA-E programs are represented in our data.

Office of Science awards to Higher Ed. awardees come mostly from the following programs: Biological & Environmental Research, Basic Energy Sciences, and High Energy Physics, and Advanced Scientific Computing Research (Table A3). EERE is also organized into multiple program offices (such as Advanced Manufacturing, Solar, and Vehicles), yet we are not able to observe these different award origins in our data. In the USAspending.gov data, EERE awards are labeled either "Conservation R&D" and Renewable Energy R&D."

In the Web of Science (WOS), we searched all indices in the WOS Core Collection, including the Science Citation Index Expanded and the Conference Proceedings Citation Index- Science. Search terms for WOS were formatted as follows: *FT = AR0000001 OR FT = AR 0000001* for award number DE-AR0000001. Patent outputs were downloaded from the US Patent and Trademark Office (USPTO) using search terms formatted as follows: *GOVT/AR0000001 OR GOVT/"AR 0000001" OR GOVT/AR0000001$ OR GOVT/"AR 0000001"$* for award number DE-AR0000001.

We use the Cooperative Patent Classification (CPC) system to identify whether each patent related specifically to Operations and Transport (B section), Chemistry and Metallurgy (C section), Electricity (H section), and/or Emerging Cross-Sectional Technologies (Y section); those in the latter category frequently relate to climate change mitigation (European Patent Office and United States Patent and Trademark Office 2016). We also track the subject of each paper based on how WOS classifies the journal of publication: both by subject category (e.g. Physics, Chemistry, Materials Science, and Engineering) and whether the journal is in the Science Citation Index Expanded subject category "Energy & Fuels."

2. Figures and Tables

Figure A1: Office of Science Basic Energy Sciences' Depiction of DOE "Research, Development, and Deployment Continuum" (U.S. Department of Energy 2014)

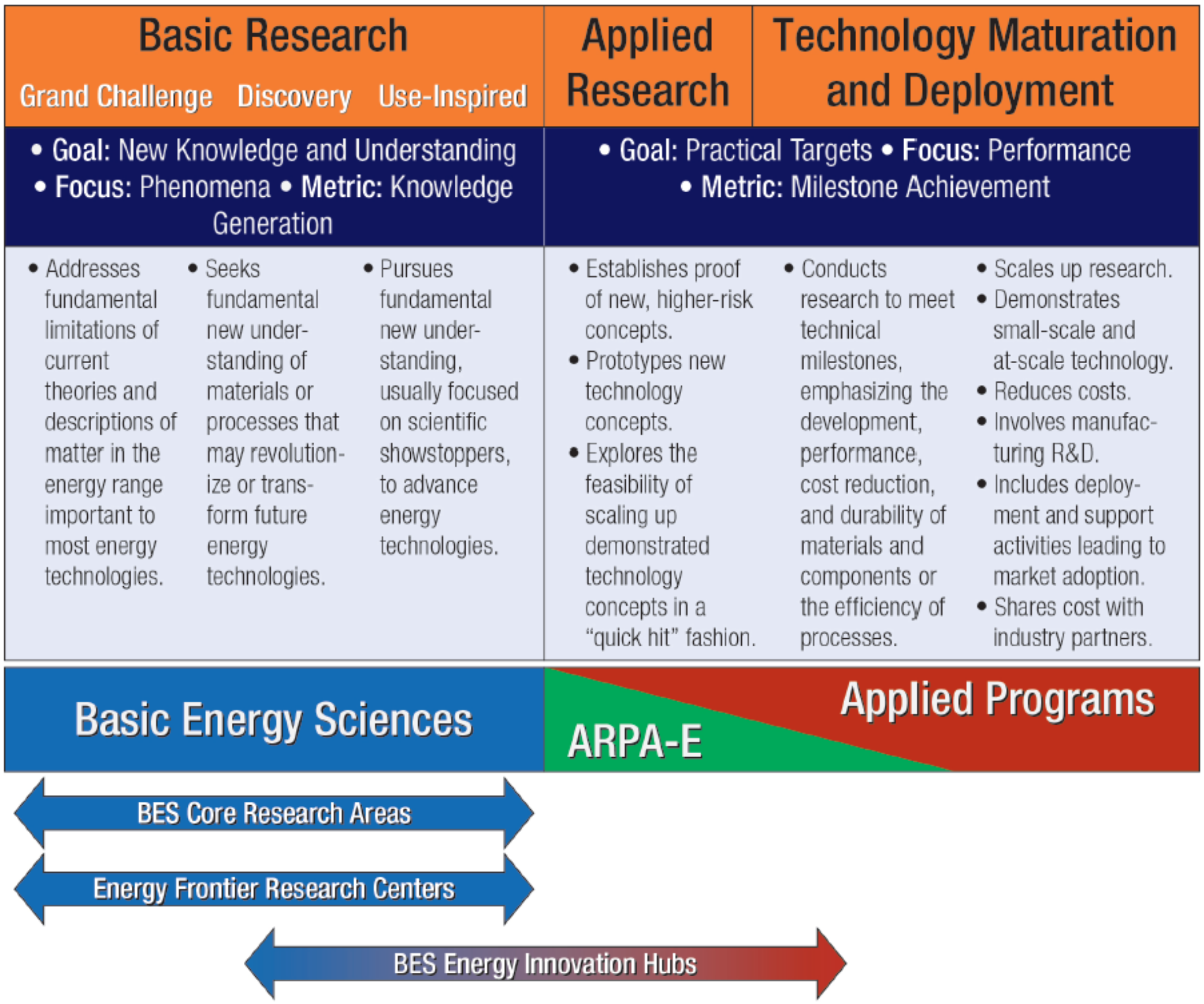


Table A1: CFDA Codes Considered Energy R&D

CFDA Number	CFDA Title	EERE Awards	Office of Science Awards
81.036	INVENTIONS AND INNOVATIONS	0	5
81.049	OFFICE OF SCIENCE FINANCIAL ASSISTANCE PROGRAM	0	2,318

81.086	CONSERVATION RESEARCH AND DEVELOPMENT	345	0
81.087	RENEWABLE ENERGY RESEARCH AND DEVELOPMENT	850	0
81.089	FOSSIL ENERGY RESEARCH AND DEVELOPMENT	1	0

Notes: Awards data are limited as described above. Counts reflect awards with net positive obligation, start and end dates between 9/30/2009 and 10/1/2015, excluding awardees labeled Government or Other.

Table A2: CFDA Codes Excluded

CFDA Number	CFDA Title	EERE Awards	Office of Science Awards
81.042	WEATHERIZATION ASSISTANCE FOR LOW-INCOME PERSONS	45	0
81.079	REGIONAL BIOMASS ENERGY PROGRAMS	1	0
81.117	ENERGY EFFICIENCY AND RENEWABLE ENERGY INFORMATION DISSEMINATION, OUTREACH, TRAINING AND TECHNICAL ANALYSIS/ASSISTANCE	83	0
81.128	ENERGY EFFICIENCY AND CONSERVATION BLOCK GRANT PROGRAM	259	0
81.129	ENERGY EFFICIENCY AND RENEWABLE ENERGY TECHNOLOGY DEPLOYMENT, DEMONSTRATION AND COMMERCIALIZATION	1	0

Notes: Awards data are limited as described above. Counts reflect awards with net positive obligation, start and end dates between 9/30/2009 and 10/1/2015, excluding awardees labeled Government or Other.

Table A3: Recipient Type by Program Office in Office of Science

Program Office	**For-Profit**	**Higher Ed.**	**Non-Profit**	**Total**
Unknown	3	9	4	16
Office of Advanced Scientific Computing Research	12	112	4	128
Office of Basic Energy Sciences	1	198	134	333
Office of Biological & Environmental Research	15	330	119	464
Office of Fusion Energy Sciences	6	54	5	65
Office of High Energy Physics	2	139	10	151
Office of Nuclear Physics	2	49	5	56
Office of Workforce Development for Teachers and Scientists	0	1	1	2
Office of the Deputy	0	0	2	2
SBIR and STTR Programs Office	1,105	1	0	1,106
Total	1,146	892	284	2,323

Figure A2: Patents Attributed to DOE Awards Dataset

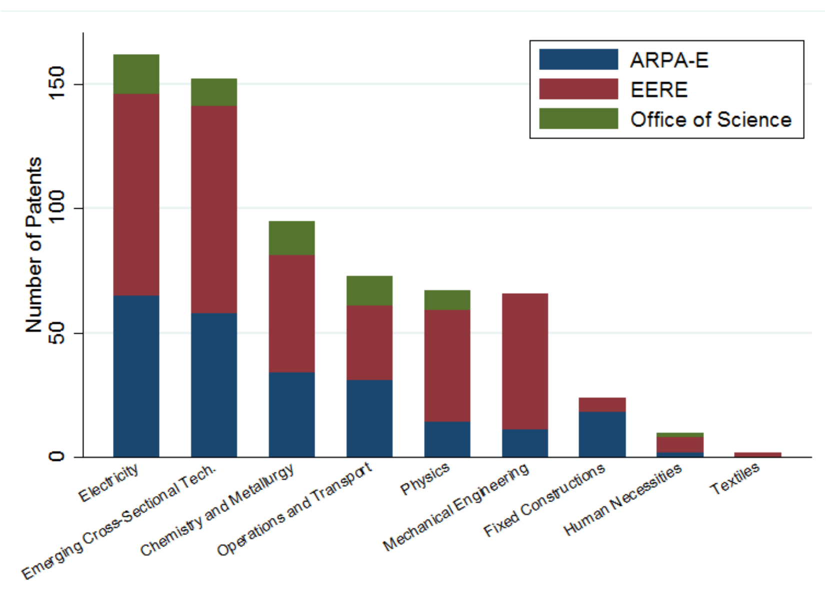


Figure A3: Publications Attributed to DOE Awards Dataset

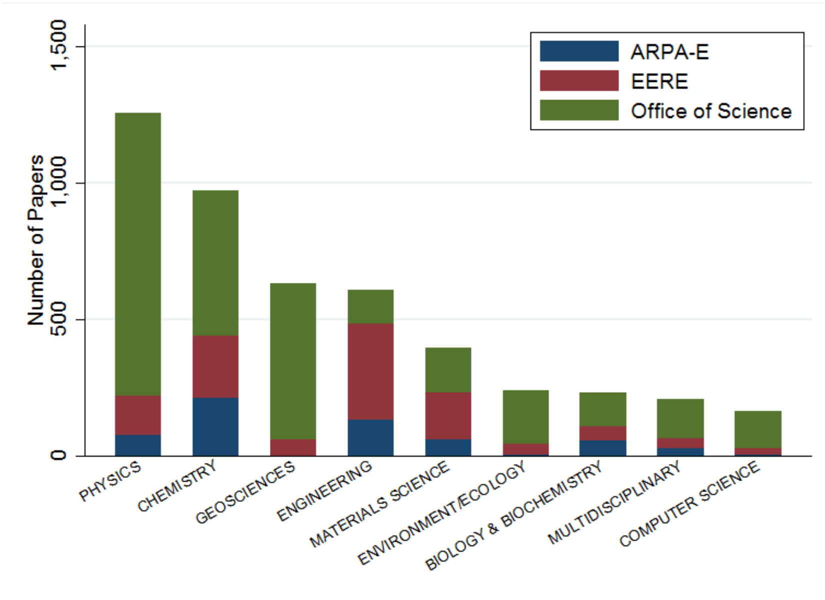
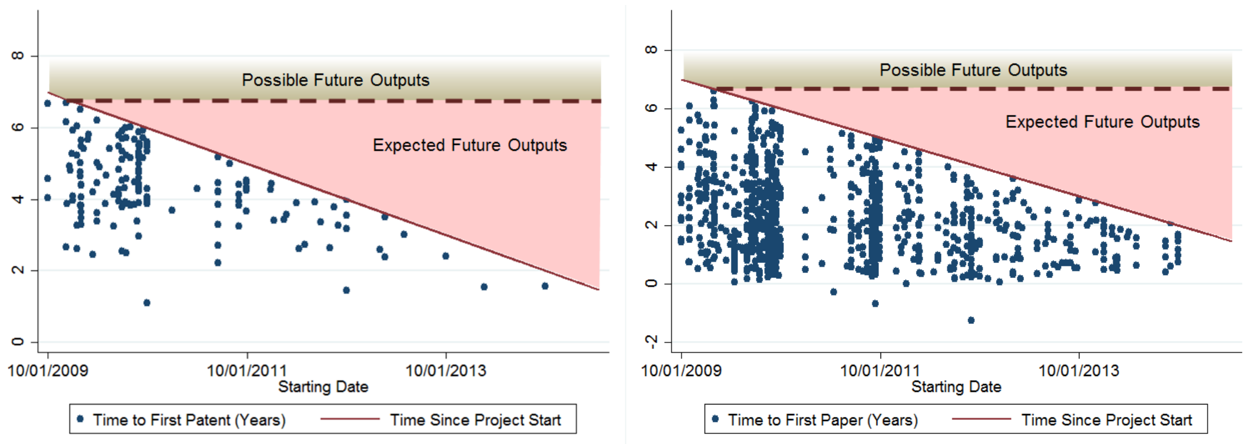


Table A4: Control Variable Testing for Award Amount

Dependent Variable: At least 1 patent and at least 1 publication	(1)	(2)	(3)
Sub-sample:	ARPA-E	EERE	Office of Science
Net Obligation	1.264**	1.283***	1.829***
	(0.121)	(0.082)	(0.367)
Org. Type F.E.	Y	Y	Y
Fiscal Year F.E.	Y	Y	Y
N	223	1025	1079
Pseudo R^2	0.117	0.051	0.047
Ln(Net Obligation)	2.257***	1.913***	2.540***
	(0.660)	(0.374)	(0.636)
Org. Type F.E.	Y	Y	Y
Fiscal Year F.E.	Y	Y	Y
N	223	1025	1079
Pseudo R^2	0.132	0.063	0.090

Notes: Robust standard errors in parentheses. All models are logit, and results are exponentiated (odds ratios).
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Figure A4: Lag Time for Observation of First Patent and First Publication



Note: Only awards with patents or publications are plotted. The triangular shaded area indicates where additional outputs are likely to accrue from the awards as time goes on, based on the maximum observed lag for patents (6.7 years) and papers (6.6 years). The top shaded area indicates where even more outputs may yet be observed, if more patents or papers continue to accrue at 7 or more years after the beginning of the award.

Table A5: Outputs from ARPA-E and EERE with Coarsened Exact Matching on Funding Amount

Dependent Variable:	At least 1 patent and at least 1 publication	At least 1 patent	At least 1 publication
	(1)	(2)	(3)
EERE	0.174***	0.229***	0.350***
	(0.075)	(0.091)	(0.095)
Ln(Net Obligation)	2.131***	1.973***	1.661***
	(0.351)	(0.222)	(0.122)
For-Profit	0.533	2.005*	0.116***
	(0.237)	(0.750)	(0.036)
Non-Profit	0.353	1.824	0.578
	(0.389)	(1.246)	(0.319)
EERE · For-Profit	1.552	1.395	1.197
	(0.869)	(0.646)	(0.417)
EERE · Non-Profit	3.632	0.802	0.324*
	(4.319)	(0.633)	(0.195)
Fiscal Year F.E.	Y	Y	Y
N	1331	1450	1450
Pseudo R^2	0.110	0.137	0.181

Notes: Robust standard errors in parentheses. All models are logit, and results are exponentiated (odds ratios). Base office is ARPA-E and base org. type is Higher Ed. Within the subsample of ARPA-E and EERE awards, we performed coarsened exact matching (CEM) on the log of obligation amount, using the *cem* package for Stata (Blackwell et al. 2009; Iacus, King, and Porro 2011). We allowed the algorithm to determine binning using Sturge's rule, and then we used the weights obtained from CEM as importance weights for the logit regressions.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A6: Outputs from ARPA-E and Office of Science with Coarsened Exact Matching on Funding Amount

Dependent Variable:	At least 1 patent and at least 1 publication	At least 1 patent	At least 1 publication
	(1)	(2)	(3)
Office of Science	0.020***	0.021***	0.934
	(0.010)	(0.010)	(0.228)
Ln(Net Obligation)	1.849***	1.729***	1.481***
	(0.435)	(0.307)	(0.067)
For-Profit	0.557	2.101*	0.128***
	(0.255)	(0.815)	(0.040)
Non-Profit	0.264	1.410	0.568
	(0.291)	(0.974)	(0.306)
Office of Science · For-Profit	24.672***	9.468***	1.141
	(17.388)	(5.640)	(0.384)
Office of Science · Non-Profit	--	--	0.751
			(0.421)
Fiscal Year F.E.	Y	Y	Y
N	2048	2244	2443
Pseudo R^2	0.256	0.339	0.154

Notes: Robust standard errors in parentheses. All models are logit, and results are exponentiated (odds ratios). Base office is ARPA-E and base org. type is Higher Ed. Within the subsample of ARPA-E and Office of Science awards, we performed coarsened exact matching (CEM) on the log of obligation amount, using the *cem* package for Stata (Blackwell et al. 2009; Iacus, King, and Porro 2011). We allowed the algorithm to determine binning using Sturge's rule, and then we used the weights obtained from CEM as importance weights for the logit regressions.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A7: Outputs From a Restricted Sample of Research Awards

Dependent Variable:	At least 1 patent and at least 1 publication	At least 1 patent	At least 1 publication
	(1)	(2)	(3)
EERE	0.357**	0.330**	0.908
	(0.172)	(0.143)	(0.188)
Office of Science	0.124***	0.103***	1.505**
	(0.055)	(0.042)	(0.248)
Ln(Net Obligation)	2.134***	1.985***	1.779***
	(0.311)	(0.193)	(0.060)
For-Profit	0.666	1.997**	0.144***
	(0.276)	(0.656)	(0.032)
Non-Profit	0.342	1.509	0.617
	(0.389)	(1.023)	(0.253)
EERE · For-Profit	1.504	1.720	0.729
	(0.895)	(0.829)	(0.216)
EERE · Non-Profit	5.213	1.518	0.433
	(6.835)	(1.360)	(0.240)
Office of Science · For-Profit	1.098	1.899	0.616**
	(0.714)	(0.887)	(0.147)
Office of Science · Non-Profit	--	--	0.682
			(0.300)
Fiscal Year F.E.	Y	Y	Y
N	3712	5087	5316
Pseudo R^2	0.217	0.285	0.241

Notes: Robust standard errors in parentheses. All models are logit, and results are exponentiated (odds ratios). Base office is ARPA-E and base org. type is Higher Ed. Awards that were marked as non-R&D in communications from EERE were excluded. Awards with the words “workshop” or “conference” in the project description were also excluded.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A8: Outputs From Expanded Sample Including Active Awards as of Oct. 1, 2015

Dependent Variable:	At least 1 patent and at least 1 publication as of Oct. 1, 2015	At least 1 patent as of Oct. 1, 2015	At least 1 publication as of Oct. 1, 2015
	(1)	(2)	(3)
EERE	0.168***	0.161***	0.545***
	(0.111)	(0.106)	(0.107)
Office of Science	0.235**	0.195***	1.328
	(0.135)	(0.109)	(0.238)
Ln(Net Obligation · Fraction of	2.244***	1.884***	1.852***
Project Elapsed as of Oct. 1, 2015)	(0.379)	(0.206)	(0.059)
For-Profit	0.471	2.448*	0.125***
	(0.299)	(1.207)	(0.031)
Non-Profit	0.793	3.059	0.704
	(0.945)	(2.363)	(0.323)
EERE · For-Profit	4.804*	3.407*	1.093
	(4.108)	(2.463)	(0.323)
EERE · Non-Profit	2.260	0.774	0.157***
	(3.206)	(0.812)	(0.082)
Office of Science · For-Profit	1.486	1.515	0.757
	(1.325)	(0.980)	(0.204)
Office of Science · Non-Profit	--	--	0.601
			(0.291)
Fiscal Year F.E.	Y	Y	Y
N	4416	5209	6535
Pseudo R^2	0.181	0.240	0.276

Notes: Robust standard errors in parentheses. All models are logit, and results are exponentiated (odds ratios). Base office is ARPA-E and base org. type is Higher Ed. We scale the amount of funding obligated by the proportion of time that has elapsed in the project as of the end of FY 2015, and we cut off observation of outputs on that date as well.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A9: Joint Output of Patent and High Impact Publication

Dependent Variable:	At least 1 patent and at least 1 "highly cited" publication (1)	At least 1 patent and at least 1 "top journal" publication (2)
EERE	0.491	0.201**
	(0.379)	(0.156)
Office of Science	0.106*	0.405
	(0.129)	(0.270)
Ln(Net Obligation)	3.323***	3.094***
	(0.990)	(0.796)
For-Profit	0.429	0.449
	(0.313)	(0.272)
Non-Profit	1.178	0.718
	(1.471)	(0.869)
EERE · For-Profit	0.385	0.601
	(0.422)	(0.652)
EERE · Non-Profit	0.310	0.774
	(0.514)	(1.292)
Office of Science · For-Profit	2.366	--
	(3.902)	
Office of Science · Non-Profit	--	--
Fiscal Year F.E.	Y	Y
N	3197	2172
(Pseudo) R^2	0.255	0.211

Notes: Robust standard errors in parentheses. All models are logit, and results are exponentiated (odds ratios). Base office is ARPA-E and base org. type is Higher Ed.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A10: Patent Outputs by Type

Dependent Variable:	At least 1 patent for Emerging Cross-Sectional Technologies	At least 1 patent for Chemistry and Metallurgy	At least 1 patent for Electricity	At least 1 patent for Operations and Transport
	(1)	(2)	(3)	(4)
EERE	0.137***	0.143***	0.229***	0.370
	(0.078)	(0.089)	(0.130)	(0.299)
Office of Science	0.019***	0.108***	0.134***	0.221*
	(0.021)	(0.074)	(0.085)	(0.197)
Ln(Net Obligation)	2.013***	2.267***	1.999***	1.884***
	(0.272)	(0.322)	(0.256)	(0.293)
For-Profit	1.126	0.672	1.672	3.014*
	(0.464)	(0.331)	(0.721)	(1.993)
Non-Profit	1.569	1.299	0.578	6.888**
	(1.221)	(1.132)	(0.606)	(6.441)
EERE · For-Profit	3.179*	2.319	1.483	0.823
	(1.967)	(1.724)	(0.930)	(0.715)
EERE · Non-Profit	0.725	1.452	--	0.163
	(0.768)	(1.612)		(0.208)
Office of Science · For-Profit	6.416	3.619*	0.951	0.994
	(7.388)	(2.820)	(0.688)	(0.935)
Office of Science · Non-Profit	--	--	--	--
Fiscal Year F.E.	Y	Y	Y	Y
N	3240	3491	3012	3491
(Pseudo) R^2	0.246	0.193	0.201	0.170

Notes: Robust standard errors in parentheses. All models are logit, and results are exponentiated (odds ratios). Base office is ARPA-E and base org. type is Higher Ed.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A11: Publication Outputs by Category

Dependent Variable:	At least 1 energy journal publication	At least 1 publication in Physics	At least 1 publication in Chemistry	At least 1 publication in Materials Science	At least 1 publication in Engineering
	(1)	(2)	(3)	(4)	
EERE	1.195	0.521**	0.346***	0.576*	1.728*
	(0.357)	(0.161)	(0.101)	(0.179)	(0.532)
Office of Science	0.205***	1.775**	0.749	0.427***	0.512**
	(0.069)	(0.499)	(0.201)	(0.135)	(0.168)
Ln(Net Obligation)	1.810***	1.602***	1.811***	1.533***	1.748***
	(0.134)	(0.083)	(0.113)	(0.106)	(0.118)
For-Profit	0.260***	0.163***	0.258***	0.111***	0.485*
	(0.101)	(0.075)	(0.089)	(0.058)	(0.181)
Non-Profit	0.563	0.970	1.592	0.927	0.458
	(0.398)	(0.604)	(0.892)	(0.582)	(0.373)
EERE · For-Profit	0.452*	1.015	0.699	2.601	0.317***
	(0.208)	(0.583)	(0.321)	(1.531)	(0.138)
EERE · Non-Profit	0.160**	0.100**	0.105***	0.043***	0.277
	(0.135)	(0.096)	(0.081)	(0.051)	(0.248)
Office of Science ·	1.346	1.339	0.532	1.867	0.820
For-Profit	(0.714)	(0.658)	(0.222)	(1.136)	(0.371)
Office of Science ·	0.408	0.136**	0.140***	0.207	0.509
Non-Profit	(0.511)	(0.106)	(0.101)	(0.199)	(0.558)
Fiscal Year F.E.	Y	Y	Y	Y	Y
N	3775	3729	3775	3775	3775
(Pseudo) R^2	0.234	0.148	0.184	0.136	0.183

Notes: Robust standard errors in parentheses. All models are logit, and results are exponentiated (odds ratios). Base office is ARPA-E and base org. type is Higher Ed.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$