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

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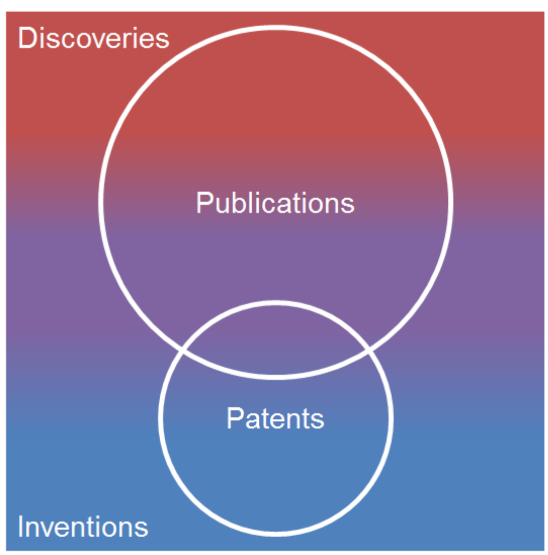
Abstract

The division of "basic" and "applied" research is embedded in federal R&D policy, exemplified by the separation of science and technology in the organizational structure of the US Department of Energy (DOE). In this work, we consider a branch of DOE that shows potential to operate across this boundary: the Advanced Research Projects Agency – Energy (ARPA-E). We construct a novel dataset of nearly 4,000 extramural financial awards given by DOE from 2010 to 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 more likely to jointly produce both a publication and a patent, with at least 5 times higher odds. ARPA-E awards have been productive in creating new technology, without a detrimental effect on the production of new scientific knowledge. This observation suggests the unity of research activities which are often considered separate: that which produces discoveries and that which produces inventions.



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1. Introduction

Stable, low-cost energy storage solutions are highly desirable as the electrical grid accommodates more intermittent renewable sources. In 2014, researchers at Harvard University published a letter in *Nature* showing the first proof-of-concept for an organic aqueous flow battery (Huskinson et al., 2014). The group created a flow battery with high cycling efficiency and catalyst-free carbon electrodes, using a water-soluble organic molecule. The researchers acknowledge funding from the Advanced Research Projects Agency – Energy (ARPA-E) (Er et al., 2015; Lin et al., 2015), and ARPA-E has publicly highlighted the achievements of this research project, including pending intellectual property and the active commercialization of the technology (ARPA-E, 2016).

Is the research into organic aqueous flow batteries best described as "applied research" or "basic research"? The researchers filed with the US Patent and Trademark Office (USPTO) to protect the new battery configuration as an invention, and yet they also published the same information as a discovery in the open literature and attracted a great deal of interest from the scientific community. If a single research project, conducted by the same team with the same source of external funding, generates knowledge that appears to be both "basic" and "applied" in nature, then how rigid is the boundary between these two categories? That is the central question of this paper.

The separation of "basic" and "applied" research, both in concept and in practice, has a long history. In 1945, Vannevar Bush promoted a policy of government support for "basic" research, which "is performed without thought of practical ends" (Bush, 1945). For Bush, "applied" research consisted of the "application of existing scientific knowledge to practical problems," while the goal of "basic" research was "expanding the frontiers of knowledge." A history of the linear model of innovation by Godin reveals how "basic" research came to have an elevated status by its association with "pure science", and how this hierarchy reinforced the conceptual boundary around "basic" research (Godin, 2006). Proposed alternatives to the linear model often preserve the distinction between "basic" and "applied" research while acknowledging feedback loops between the two.[1]

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[1] The Frascati Manual, published since 1963 by the Organization for Economic Cooperation and Development (OECD), is one prominent example. The manual provides guidance on how to classify and measure "basic" and "applied" research, although it takes care to avoid the linear model, noting the "many flows of information and knowledge in the R&D system" (OECD, 2015).

Beyond revising the linear concept of knowledge flows, some scholars have taken a step further and denounced the separation of “basic” and “applied” research altogether. Rosenberg observed that it is not useful to distinguish between “basic” and “applied” research on the basis of the researcher’s intentions (Rosenberg, 1990), due to the uncertainty inherent to the research process. Investigations that aim to serve a particular purpose may yield unexpected scientific breakthroughs, such as those of Pasteur and Carnot, and researchers that aim to explore new phenomena often end up inventing new technology. Nelson explored these dynamics at Bell Labs in the invention of the transistor (Nelson, 1962). Narayanamurti et al. illustrate the many other connections between discovery and invention in the development of information technology (Narayanamurti et al., 2013) and other fields (Narayanamurti and Odumosu, 2016), and they call for the recognition of research as a singular practice of both science and engineering.

Furthermore, there has been pushback on the social implications of the basic/applied dichotomy. Many have called for the abandonment of Bush’s social contract, wherein the public supports curiosity-driven research on the basis of its potential to be useful. Instead, they urge scientists to be directly motivated by, not isolated from, social problems (Byerly and Pielke Jr., 1995; Sarewitz, 2016). Donald Stokes proposed the existence of “use-inspired basic research”, where a scientist may be motivated by applications of their work and yet the outcome of their work is so-called “fundamental understanding” (Stokes, 1997). Unfortunately, the division of research effort between “basic” and “applied” has become a highly politicized issue (Anadón et al., 2016). Those in favor of small government want to limit public support for “applied” research, which is presumed to be the domain of the private sector. Very few programs exist that can pursue research aimed at both discovery and invention.

The separation of “basic” and “applied” research is particularly problematic for the agencies which are charged with achieving practical missions, such as the Department of Energy (DOE). Most of DOE’s research funding is organized around a dividing line between “basic” research and all other activities, though there is one branch of DOE that has shown the potential to break through this divide: the Advanced Research Projects Agency – Energy (ARPA-E). ARPA-E’s mission is to fund “transformative” research and development (R&D) on clean energy technology, and it operates outside of the bureaucratic structure that funds all other R&D at DOE.

In this paper, we consider the joint production of publications and patents to be evidence of the overlap between “basic” and “applied” research, and we ask how frequent this outcome was for ARPA-E awards relative to awards given by other branches of DOE. We find that, in its first six years, ARPA-E has been highly effective in encouraging research teams to simultaneously produce discoveries and inventions. This finding demonstrates that scientific discovery is not strictly the domain of “basic” research programs and that the division of "basic" and "applied" is not necessary as an organizing principle for research funding organizations.

The next section reviews the organizational structure that supports the division between "basic" and "applied" research at DOE, the role of ARPA-E within DOE, and our chosen metrics of research outputs. In Section 3, we describe our empirical approach of assessing R&D awards from funding organizations within 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 "basic"/"applied" dichotomy at the Department of Energy

Among its many functions, including nuclear security and nuclear waste management, DOE spends billions of dollars on R&D each year. In 2014, the federal budget for R&D at DOE was approximately $12 billion, divided among three budget functions: $4.7 billion for "General science"[2], $5.0 billion for "National defense" and $2.3 billion for "Energy" (National Science Foundation and National Center for Science and Engineering Statistics, 2015). DOE's Office of Science administers all its "General science" spending, and the "Energy" budget is divided between ARPA-E and four offices devoted to specific technology areas, the largest of which is the Office of Energy Efficiency and Renewable Energy (EERE), with a 2014 budget of $870 million (National Science Foundation and National Center for Science and Engineering Statistics, 2015).[3]

According to DOE's 2017 budget request to Congress, the Office of Science funds "basic research programs," and EERE funds "applied research, development, demonstration and deployment activities" (U.S. Department of Energy, 2016). Repeated references to "basic research" as a separate entity from "applied energy programs" reinforce the conceptual and practical division of these two types of research. A commitment to reinforcing the boundary around "basic" research has been observed in the Energy

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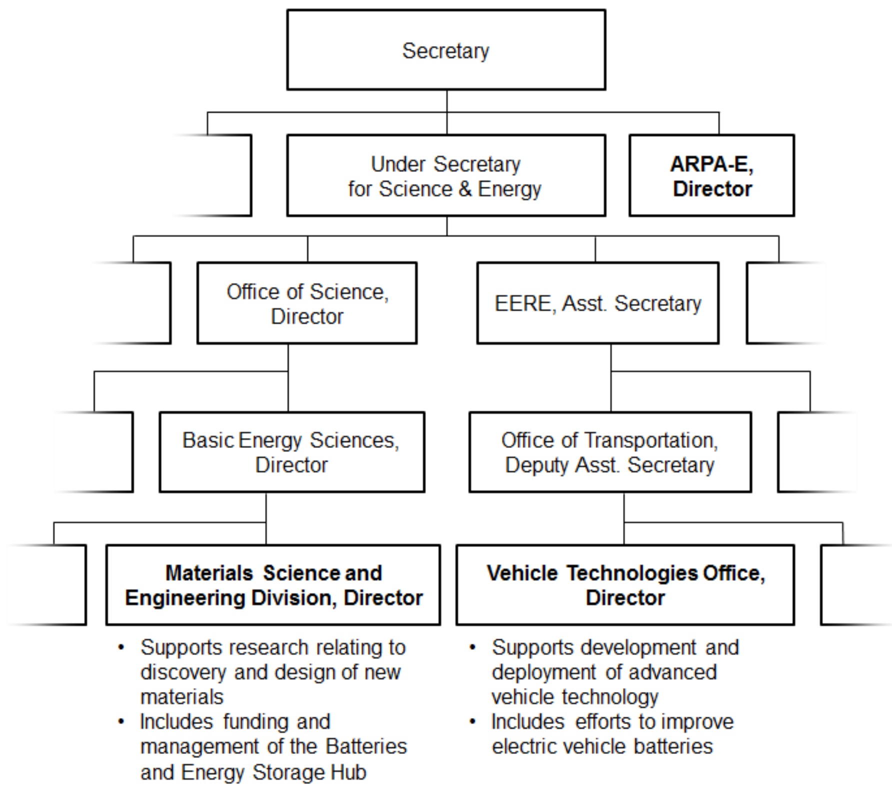
[2] Within each budget function, some federal R&D funds are further labeled as "basic research." The full name of the "General science" budget function is "General science and basic research," although several other budget functions contain significant allocations for "basic research", in particular "Health," "Agriculture," and "Space flight." As of 2014, 92% of the R&D budget in the "General science" category is considered "basic research", and the category itself only contains 27% of the federal "basic research" allocations. DOE is unique in having a large portion of its budget assigned to specific applications as well as the "General science" budget function; the only other agency with funding in the "General science" category is the National Science Foundation (NSF).

[3] The other technology offices are the Office of Nuclear Energy ($634 million), the Office of Fossil Energy ($442 million) and the Office of Electricity ($92 million).

Frontier Research Centers administered by Office of Science (Narayanamurti and Odumosu, 2016). The isolation of science from technology at DOE is also evident in the declining private sector engagement with national labs (Anadón et al., 2016).

Some recent initiatives have attempted to bridge the divides between various DOE research activities. 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.). Furthermore, 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). Nonetheless, the Office of Science and each of the "applied" programs continue to operate as separate, hierarchical organizations today. An illustrative example is shown in Figure 1, with three administrative layers between the group in Office of Science that coordinates funding for battery materials research (including the Energy Storage Hub) and the Vehicle Technologies Office in EERE, which coordinates funding for electric vehicle battery R&D and deployment.

Figure 1: Hierarchy in the Department of Energy Separates Battery Science from Battery Technology (Office of Basic Energy Sciences, 2016; Office of Energy Efficiency & Renewable Energy, 2016; U.S. Department of Energy, 2015)



2.2. ARPA-E's place in the landscape of DOE research funding

ARPA-E has been funding R&D projects in energy technology since 2009, making it the newest addition to the landscape of DOE R&D funding organizations. According to their solicitations, ARPA-E aims to fund "transformative research that has the potential to create fundamentally new learning curves". Their stated goal is "to catalyze the translation from scientific discovery to early-stage technology" (ARPA-E, 2015). The Director of ARPA-E reports directly to the Secretary of Energy. Because it exists outside the traditional DOE hierarchy (Figure 1), ARPA-E is not implicitly defined as either "basic" or "applied" by its position in the departmental structure.

There is some evidence that ARPA-E is aligned with the "applied" elements of research. ARPA-E states in its solicitations that its goal is to fund "applied research and development of new technologies" (ARPA-E, 2014). The identity of ARPA-E as an "applied" agency is also depicted in the 2014 summary report by the Basic Energy Sciences within Office of Science (U.S. Department of Energy, 2014), where the line between “basic” and “applied” research is sharp, and ARPA-E is labeled unambiguously as “applied” research. This graphic, reproduced in the Appendix, reinforces the separation of “basic” and “applied” by listing distinct goals and metrics of the two types of research.

However, the nature of ARPA-E is described elsewhere as being somewhat different from both “basic” and “applied” research at DOE. One of the means authorized by the America COMPETES Act for ARPA-E was “identifying and promoting revolutionary advances in fundamental and applied sciences,” implying that ARPA-E’s work would relate to both sides of the “basic”/“applied” dichotomy (110th Congress, 2007; 111th Congress, 2011). In the DOE 2017 budget request, ARPA-E’s role is described as “complementing and expanding the impact of DOE’s basic science and applied energy programs” (U.S. Department of Energy, 2016).

In its first annual report, ARPA-E described its program creation process in the following 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.” This same report identified ARPA-E’s purview in terms of Technology Readiness Level (TRL), “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).[4]

Further evidence of the position of ARPA-E between “basic” and “applied” research can be found in the advice they give to applicants. Since 2012, every funding solicitation from ARPA-E has included specific instructions for how 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

[4] The TRL scale was developed by NASA and adopted by the Department of Defense to assess technology maturity (U.S. Department of Energy, 2011). In 2011, ARPA-E funding opportunity announcements (FOAs) advised that “ARPA-E operates mainly within the ‘valley of death’ between TRL-3 and TRL-7” (ARPA-E, 2011), which fall in the middle of the TRL scale, comprising proof of concept, component validation, and prototype demonstration. These levels are rated as more mature than the observation of “basic” principles (TRL-1), but less mature than actual system testing and operation (TRL-8 and 9).The agency has not used technology readiness level (TRL) to describe its projects since 2012.

> of Fossil Energy, the Office of Nuclear Energy, and the Office of Electricity Delivery and Energy Reliability." (ARPA-E, 2012)

Based on the published descriptions of ARPA-E, there is evidence that the agency serves a connector or an "in-between" funding source, for projects that are too technology-focused to be considered "basic" research but are too novel to be considered "applied" research. Can we also find evidence of ARPA-E's orientation between "basic" and "applied" research in the output of the agency during its first several years of operation? To do so, we must select metrics for assessing the output of research funding programs.

2.3. Metrics of knowledge creation

New knowledge is the goal of research, whether research is classified as "basic" or "applied" or not classified at all. While we are not able to directly measure knowledge creation, we can measure the portion of new knowledge that is disclosed through both publications and patents. New knowledge of a natural phenomenon (i.e. *discovery*) is likely to be published in a peer-reviewed journal, while new knowledge of a device or usable method (i.e. *invention*) may be published, patented, or both. This taxonomy reflects the common understanding that publications are the preferred method of disclosure in the scientific community, while patents are one potential avenue for disclosure in the world of technology (Dasgupta and David, 1994; Murray, 2002).

It is important to note the possibility for overlap between these categories, such as a piece of knowledge that is both a discovery and an invention (Narayanamurti and Odumosu, 2016), or knowledge that is both published and patented (Fehder et al., 2014; Gans et al., 2013; Murray, 2002; Murray and Stern, 2007). If an agency gives a financial award that produces both a patent and a publication, then research it funded is likely to fit into "Pasteur's quadrant" at the intersection of "basic" and "applied" research (Gans and Murray, 2012; Stokes, 1997). The joint output of these disclosures is meaningful with respect to the nature of the research project, which was supported by the same funding source under one proposal by the same team of researchers, even when the award-linked publications and patents disclose different pieces of knowledge.

In this work, we take the existence of awards with joint outputs of patents and publications as evidence of the overlap between discovery and invention within a single award. We measure the frequency of these awards in order to understand the relative importance of this overlap in DOE-funded research. A more accurate measure of an award's impact on the state of science or technology would involve measuring, not just the raw counts, but their citation-weighted impact. Given the short time that has elapsed since the study period, we are limited in what citation data are available, yet we do include measures of "citedness" as a robustness check.

One concern over using publications and patents as indicators of research progress is that they could overstate the value of 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, the fact that an awardee received a patent does not indicate a useful invention. The barrier for patenting may also be relatively low, due to either low or inconsistently applied standards (Rassenfosse et al., 2016), and issued patents have a low probability of ever being licensed or litigated (Lemley and Shapiro, 2005).

On the other hand, it is clear that rates of patenting and publishing do not capture the full value of research support from public agencies. Each project may contribute directly to the knowledge that is accrued and transferred between researchers and between institutions, whether or not it produces a measurable output *per se*. Award funds may be used to support graduate student training, which amounts to an investment in future knowledge production as those students advance in their own careers. Furthermore, inventions resulting from an R&D award may not be disclosed at all, if they are instead held as trade secrets by private sector awardees, or when the cost of pursuing a patent is too high for academic and non-profit organizations.

Despite these limitations, we believe there is meaningful information to be obtained from comparing the discoveries and inventions produced by awardees. In order for discoveries to impact the scientific community, they must be published; therefore, publishing indicates the potential for impact. Similarly, patenting is a signal of potential commercial value for an invention. In other words, it is unlikely for a research project to have a major long-term impact with no publications or intellectual property (IP) whatsoever. Rather than speculate on the total value and impact of each award, we limit our analysis to indicators of the immediate output of the awards in terms of disclosed production, and we consider the sum of knowledge produced by a given research investment to be partially reflected by the number of publications and patents observed.

3. Empirical Approach

In this paper, we seek to understand ARPA-E's contribution to energy research, in the context of DOE R&D funding as a whole. ARPA-E has a unique mission within DOE to pursue early-stage energy technology with the potential to be "transformational"; 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 technology offices. Because ARPA-E has the greatest subject matter overlap with EERE among the technology offices, we choose Office of Science and EERE as the two groups for comparison for ARPA-E.

Our goal is not to judge the value of the awards from these offices in a competitive sense, but rather to understand ARPA-E's contribution to energy innovation alongside the rest of the DOE's R&D efforts. Furthermore, because EERE and Office of Science are distinct in their missions and approaches, we compare awards from each organization separately to ARPA-E, rather than making direct comparisons between the two.

The strongest points of comparison for ARPA-E within DOE are those that directly fund R&D projects, and as such, we do not consider the funding that is distributed by DOE via contracts. This exclusion is important to note, because contracts are the primary mechanism for funding research at the national labs.[5] Cooperative agreements, which ARPA-E uses as its primary mechanism of distributing funds, are different from grants in that they entail "substantial involvement" between the agency and the recipient. We choose grants and cooperative agreements (referred to collectively in this paper as "awards") as the most relevant basis for comparison to ARPA-E.

Transaction data for prime recipients of grants or "other financial assistance" were obtained from USAspending.gov for the fiscal years (FY) 2009-2015, and these transactions were combined to arrive at a dataset of financial awards given by DOE. We focus our analysis on those awards given by ARPA-E, EERE, and Office of Science,[6] and we removed duplicate transactions with the same award number and same funding amount in the same fiscal year.

We also 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

[5] 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).

[6] 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.

Catalog of Federal Domestic Assistance (CFDA). These titles are quite broad and do not allow fine segmentation of specific activities, so we are not able to systematically exclude some non-research funding, such as support for training, outreach, conferences. A list of the CFDA numbers considered here to be within the scope of energy R&D, as well as those that were excluded, is included 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. Many Office of Science awards in particular were still active as of Oct. 1, 2015, because they are often renewed at the end of a funding cycle if they are judged successful. Removing these awards could bias the estimation in favor of ARPA-E, which does not renew awards, so we test the effect of this exclusion in the Appendix.
- **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, as they had obligation amounts of up to several hundred million USD. This exclusion ensures that any comparisons that account for the effect of funding level will have common support across both ARPA-E and non-ARPA-E awards.
- **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 3,774 awards (256 from ARPA-E, 1,197 from EERE, and 2,322 from Office of Science) and accounts for over $3 billion in financial assistance.

We check the quality of our processed data by comparing to alternative data sources on a subset of awards, obtained from the ARPA-E and Office of Science 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. Meanwhile, the 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. 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.

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. According to the USAspending.gov data, EERE awards are split between the rough categories of "Conservation R&D" and Renewable Energy R&D." A breakdown of awards in the EERE and Office of Science programs is shown in the Appendix.

We supplement our dataset with 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,[7] and patent outputs were downloaded from the US Patent and Trademark Office (USPTO).[8] 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, each of which acknowledges a single award in our dataset, and 5,181 publications, 16 of which acknowledge awards in our dataset from two offices.[9]

We investigate 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 during the observation period. We also take advantage of 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

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[7] We searched all citation 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, e.g. *FT = AR0000001 OR FT = AR 0000001* for award number DE-AR0000001

[8] Search terms for USPTO were formatted as follows, e.g. *GOVT/AR0000001 OR GOVT/"AR 0000001" OR GOVT/AR0000001$ OR GOVT/"AR 0000001"$* for award number DE-AR0000001

[9] Of these, 4 are jointly sponsored by ARPA-E and EERE, 4 by ARPA-E and Office of Science, and 8 by EERE and Office of Science.

frequently relate to climate change mitigation (European Patent Office and United States Patent and Trademark Office, 2016).

For publications, we measure their 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 top 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. Finally, we track which awards produced publications in journals categorized by WOS under specific subject areas (e.g. Physics, Chemistry, Materials Science, and Engineering), and which awards published in a journal from the Science Citation Index Expanded subject category “Energy & Fuels.”

4. Results

We begin with a simple strategy for comparing the R&D awards in our dataset: compare the mean value of several outputs across ARPA-E, EERE, and Office of Science. The results of these comparisons are shown in Table 1. The set of ARPA-E awards as a whole has greater output per award with respect to each of the variables listed, compared to EERE and Office of Science awards in the dataset. For example, the mean value of “At least 1 patent” is 0.20 for ARPA-E awards, meaning that 20% of ARPA-E awards produced a patent in our observation period. Nearly half of ARPA-E awards (48%) produced a publication.

Table 1: Summary Statistics for ARPA-E Awards Compared to EERE and Office of Science

Variable	Mean	S.D.	Min.	Max.	**t[d] (ARPA-E – Office of Science)**	**t (ARPA-E – EERE)**
Net obligation (mil. USD)	2.36	1.88	0.01	10.20	**7.85**	**16.41**
Project duration (years)	2.46	1.08	0.27	5.49	**-2.12**	**6.80**
Joint Outputs						
At least 1 patent and at least 1 publication[a]	0.11	0.31	0	1	**4.02**	**5.20**
At least 1 output (either patent or publication)	0.57	0.50	0	1	**9.87**	**9.17**
Patents						
Number of patents	0.52	1.78	0	23	**3.25**	**4.56**
At least 1 patent	0.20	0.40	0	1	**5.44**	**7.44**
Emerging Cross-Sectional Technologies	0.13	0.34	0	1	**4.33**	**5.97**
Chemistry and Metallurgy	0.08	0.27	0	1	**3.46**	**4.30**
Electricity	0.12	0.33	0	1	**4.37**	**5.64**
Operations and Transport	0.07	0.26	0	1	**3.31**	**4.19**
At least 1 cited patent	0.06	0.24	0	1	**2.88**	**4.03**
Publications						
Number of publications	2.42	4.60	0	42	**4.61**	**2.87**
At least 1 publication	0.48	0.50	0	1	**7.99**	**6.39**
Energy & Fuels journal	0.16	0.37	0	1	**2.68**	**6.29**
Physics	0.14	0.34	0	1	**4.18**	**1.49**
Chemistry	0.23	0.42	0	1	**6.59**	**6.22**
Materials Science	0.13	0.34	0	1	**3.33**	**4.70**
Engineering	0.16	0.36	0	1	**1.56**	**5.30**
At least 1 highly cited publication[b]	0.13	0.34	0	1	**4.26**	**3.55**
At least 1 top journal publication[c]	0.18	0.38	0	1	**5.54**	**3.94**

[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[b] from 2006-2016
[d] Two-tailed t-test for equality of means between the two groups, allowing for unequal variance

By performing a t-test (allowing for unequal variance), we establish that the difference in means between ARPA-E and the other offices are positive on all outputs, and nearly all these differences are significant with 99% confidence ($t > 2.6$). However, as will be immediately obvious to anyone familiar with these three organizations, the awards given by ARPA-E are dissimilar in many ways from those given by both EERE and Office of Science. One important factor is in the size of the award; even after excluding awards outside the range of funding amounts for ARPA-E, the ARPA-E awards in our dataset are on average larger than either the Office of Science awards or the EERE awards. Because the amount of money devoted to a project is likely to impact its ability to yield papers and patents, we include order of magnitude of funding as a control variable. In the Appendix, we test the use of coarsened exact matching to reduce imbalance in funding amount across the three groups.

Other aspects of the awards in our dataset could impact their productivity, such as the year in which the award was given. There is a significant time lag involved in the production of both papers and patents; in the Appendix, we illustrate the lag between the beginning of each award and the first observed 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.

We model the probability of binary output variables using logistic regression, including control variables to account for the expected variation described above. These regressions are based on the form in Equation 1, where 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) $$logit\left(P\left(Y_{ijk}\right)\right) = \beta_0 + \beta_1 X_i + \beta_2 \ln(funding\ amount_i) + \varphi_j + \gamma_k$$

For logit regressions, the quantity listed in the table is the exponentiated coefficient, 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.

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 production of publication and patents is rare, occurring in only 70 of 3,775 (1%) of awards. However, the proportion does vary by office; 10.5% of ARPA-E awards achieve both, compared to 0.5% of Office of Science awards and 2.6% of EERE awards. To illustrate the diverse types of organizations and research areas being supported by the awards in our dataset, examples of awards producing these joint outputs are shown in Table 2.

Table 2: Example Awards with Joint Outputs (Patents and Publications)

Office	Recipient	Description	FY Start	Obligation (million USD)	Number of Patents	Number of Publications
ARPA-E	Oregon State University	Natural Gas Vehicle Self-Contained Home Filling Station	2013	1.00	1	1
ARPA-E	Ginkgo Bioworks, Inc.	Engineering E. Coli As An Electrofuels Chassis For Isooctane Production	2010	6.44	1	6
ARPA-E	General Electric Company	CO_2 Capture Process Using Phase-Changing Absorbents	2011	3.72	3	4
EERE	US Synthetic Corporation	The Development Of Open, Water Lubricated Polycrystalline Diamond Thrust Bearings For Use In Marine Hydrokinetic Energy Machines	2010	0.14	1	1
EERE	General Electric Company	Recovery Act Optimized Phosphors For Warm White LED Light Engines	2010	1.74	2	3
EERE	Arizona State University	Solid State Lighting - High Efficiency And Stable White OLED Using A Single Emitter	2012	0.66	1	13
Office of Science	Aspen Aerogels, Inc.	Superhydrophobic Aerogel As Sorbent Material For CO_2 Capture	2010	1.10	1	1
Office of Science	Euclid Techlabs, LLC	Metal Plasmonic Nanostructure Functionalized By Atomic Layer Deposition Of 2A Metal-Oxides For Robust High-Quantum-Efficiency Ultrafast Photocathodes	2013	0.15	1	1
Office of Science	University Of California, Los Angeles	Microfluidics Without Channels: Highly-Flexible Synthesis On A Digital-Microfluidic Chip For Production Of Diverse Pet Tracers	2010	1.20	1	8

Note: Three awards were randomly selected for each of the three offices from those that produced at least 1 patent and at least 1 publication.

Regression analysis shows that ARPA-E has a broad positive advantage on the joint output of publications and patents (Table 3). This result is robust to several specifications, including a fixed effect for the type of recipient and an interaction effect of recipient type and sponsoring offices. No significant differences are observed across different types of awardees. The odds ratio of a joint output for both EERE and Office of Science awards is significantly less than 1; the odds of achieving a joint output appear roughly 5 times higher for an ARPA-E award.

The OLS result (Model 4) is ~10% lower probability of a joint output for both EERE and Office of Science compared to ARPA-E, matching the sign and significance of the logit results. Additional specifications are tested in the Appendix.

Table 3: 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 (odds ratios). Base office is ARPA-E and base org. type is Higher Ed.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

This increased odds of joint outputs compared to EERE and Office of Science awards does not tell a complete story. One may still wonder whether the increase in joint outputs is due to an increase in either output individually, or perhaps both. In the next two sections, we consider patents and publications separately to demonstrate their individual frequencies across different offices.

4.2. Patents

ARPA-E awards have a significant advantage in patenting compared to similar awards from EERE and Office of Science, as shown in Table 4. Here we see some significance in the organization type fixed effects, indicating that awards to companies have an advantage in patenting over academic awardees. The odds of patenting are significantly less than 1.0 for both EERE and Office of Science compared to ARPA-

E. The effect is less significant when we measure cited patents specifically (Model 3), yet the trend suggests that the increase in patenting volume for ARPA-E is not explained by a decrease in patent quality.

Table 4: 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	0.269***	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	2.680*	1.721	0.760
	(1.604)	(1.199)	(0.880)
EERE · For-Profit	2.573*	1.911	0.735
	(1.257)	(0.953)	(0.725)
EERE · Non-Profit	0.274	0.475	--
	(0.222)	(0.434)	
Office of Science · For-Profit	1.106	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	3432	3432	3197
Pseudo R^2	0.157	0.202	0.195

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

We also compare variables that measure whether any patents were produced in specific categories under the Cooperative Patent Classification system. Of particular interest is Section Y, for "Emerging Cross-Sectional Technologies." Most of the patents in this category are labeled as "Technologies or Applications for Mitigation or Adaptation Against Climate Change." Odds of patenting in this and multiple other categories are reduced for EERE and Office of Science awards compared to ARPA-E; full results are shown in the Appendix.

4.3. Publications

Next we consider the publication-related outputs from each award in the dataset. Unlike the patenting results, here we see a divergence between the comparisons of ARPA-E with EERE and with Office of Science (Table 5). 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 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 5: 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	0.669*	0.338***	0.812	0.451**
	(0.155)	(0.093)	(0.270)	(0.139)
Office of Science	2.001***	1.004	1.814*	1.885**
	(0.433)	(0.268)	(0.589)	(0.531)
Ln(Net Obligation)	2.040***	1.944***	2.075***	1.964***
	(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	1.155	0.555	0.926	2.404
	(0.606)	(0.316)	(0.665)	(1.352)
EERE · For-Profit	0.840	1.330	0.124***	0.441
	(0.300)	(0.489)	(0.083)	(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***	0.186***
	(0.135)	(0.366)	(0.076)	(0.094)
Office of Science · Non-Profit	0.229***	0.525	0.761	0.188***
	(0.129)	(0.315)	(0.601)	(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.
* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Considering 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 both measures of high impact papers show lower odds for Office of Science For-Profit awards over ARPA-E For-Profit awards.[10]

[10] 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 (1.814 in Model 3).

The odds of publishing are also measured separately for different types of publications: journals that are labeled as Energy & Fuels, as well as the subject categories of Physics, Chemistry, Materials Science, and Engineering. ARPA-E has an advantage in publishing over Office of Science in each the subject categories except for Physics. Compared to EERE, ARPA-E has an advantage in producing Physics, Chemistry, and Materials Science publications, but equivalent rates of producing Energy & Fuels publications, and lower odds of producing Engineering publications from academic awards specifically. Full results of these comparisons are shown in the Appendix.

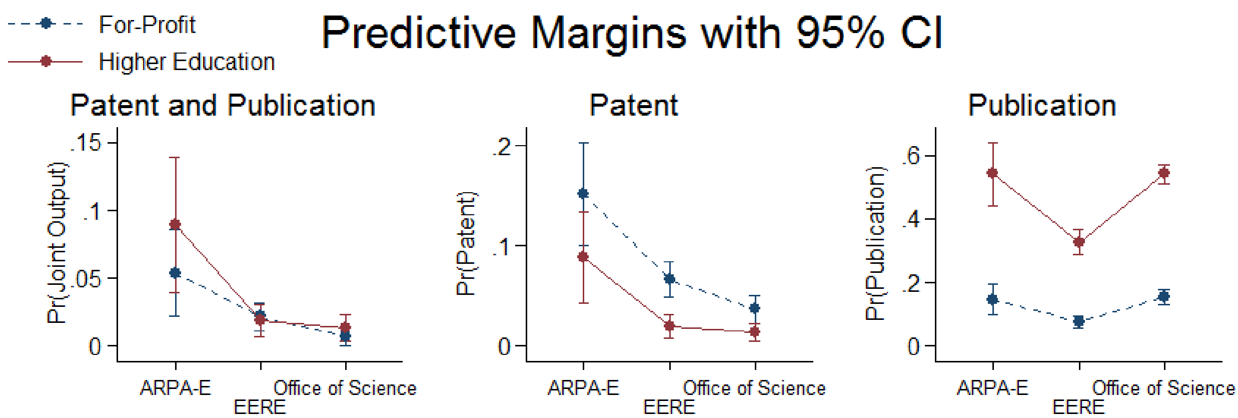
5. Discussion

As we consider the output of financial assistance from DOE, it is important to emphasize that our dataset represents a small portion of Office of Science and EERE activities, and should not be used to judge the work of each office as a whole. The Office of Science is a steward of 10 of the 17 DOE national laboratories (U.S. Department of Energy, 2016). EERE also stewards the National Renewable Energy Laboratory, while also funding a wide range of technology demonstration and deployment projects. Furthermore, because of limitations in the available data, our data include some awards for non-R&D activities (such as conferences and workshops) that would not be expected to be acknowledged in any published record.

We also note that our measurements of publication and patenting activity do not capture the full extent of ARPA-E's impact, even for the earliest cohort of awards given in FY 2010. Many awards in our dataset have pending patent applications, so the proportion of awards that are acknowledged in a patent is significantly underestimated. Some awards have led to private financing or even the release of commercial products, many of which have been documented by ARPA-E (ARPA-E, 2016); more of these market-based outcomes will surely accrue over time. Only time will tell which of these awards will eventually impact the marketplace for energy technology.

With these caveats in mind, our results provide an early assessment of ARPA-E's impact on science and technology. We highlight 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, indicating that they operate at the intersection of discovery and invention. (2) ARPA-E awards are more likely to produce IP compared to their DOE counterparts, revealing that ARPA-E is well-suited either to stimulate inventive activity or to encourage awardees to pursue IP, or perhaps both. This comparative advantage in patenting aligns well with the agency's focus on new technology. (3) The agency has produced a significant volume of scientific publications, on par with similar Office of Science awards. This is a surprising result, given the strong orientation of Office of Science toward "basic research". Our results are summarized in Figure 2, where we plot 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

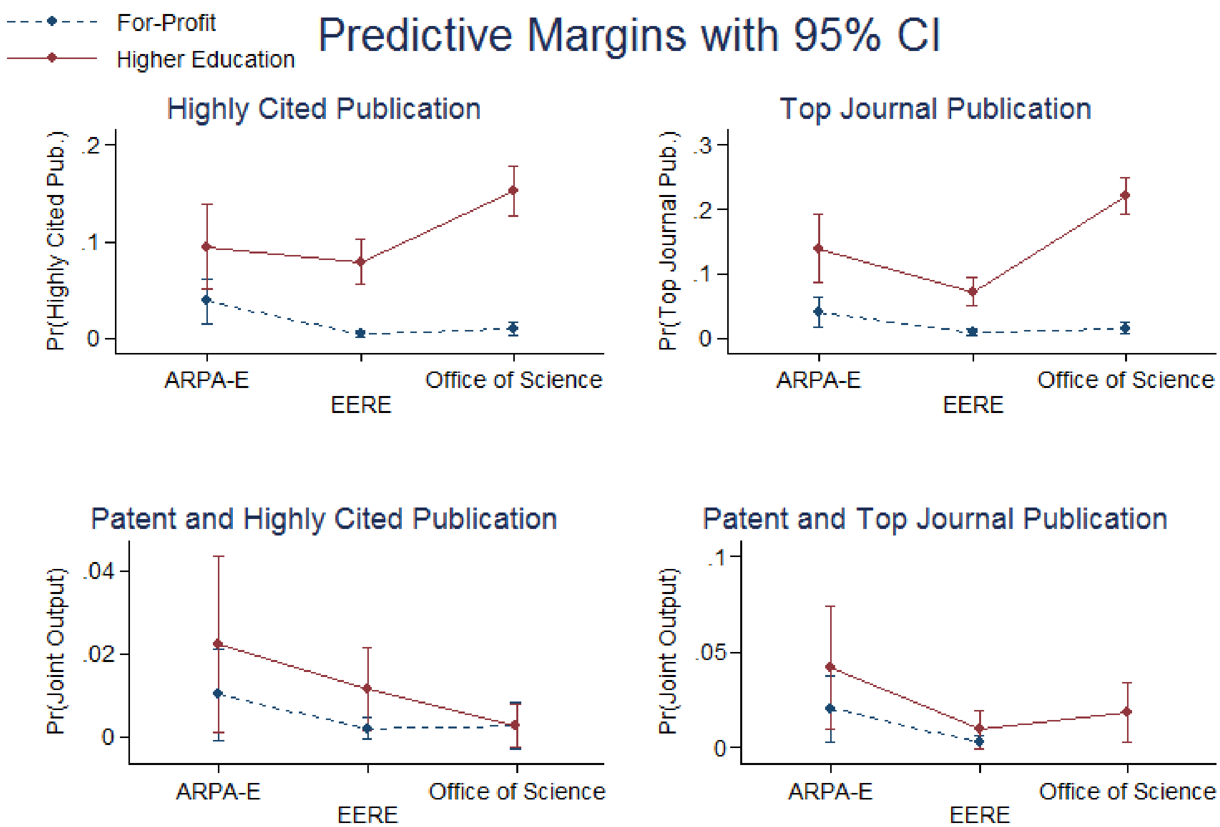


Note: Non-Profit awards are not plotted for clarity. Plots were generated by the *margins* and *marginsplot* commands in Stata (Williams, 2012). Regression data for these plots are found in (a) Table 3, Model 3; (b) Table 4, Model 2; and (c) Table 5, Model 2.

The evidence presented here suggests that ARPA-E has successfully bridged the domains of "applied research" and "basic research" by excelling in the production of patents, while matching or exceeding the performance of other funding sources at producing publications. If scientific and technological knowledge pursuits were truly at odds with each other, one would expect a tradeoff between patenting and publishing, and yet ARPA-E awardees' advantage in patenting has not diminished their ability to publish. This result is consistent with a complementary relationship between individual researchers' patenting and publishing activities (Fabrizio and Di Minin, 2008).

An alternative explanation for our findings is that the true tradeoff for increased patenting activity is not in the volume of publications, but in the quality of publications. We test this hypothesis by measuring the joint production of patents and high impact papers. Although ARPA-E awardees produce fewer high impact papers than similar Office of Science academic awardees, the probability of a joint output of at least one patent *and* at least one high impact paper is nonetheless higher for ARPA-E, as shown in Figure 3. Full regression results are shown in the Appendix.

Figure 3: Probability of Outputs with High Impact or Top Journal Publications



The evidence in this work does not directly point to a mechanism for ARPA-E's overall advantage in knowledge production. There are many programmatic differences between ARPA-E and the rest of DOE that could be responsible for our findings. One notable difference is its organizational structure, modeled after DARPA, with minimal hierarchy and individual staff members on short-term rotations, who are more substantively involved with ongoing projects and make decisions with relative freedom. ARPA-E projects are actively managed, giving program directors the opportunity to influence the outputs of the projects as they develop. Our work here does not directly test the impact of these practices, though this is an area of continuing research.

Another important difference is that ARPA-E is much smaller than EERE or Office of Science, both in terms of budget and number of awards given. Perhaps ARPA-E is able to be more selective in funding only the highest quality proposals. In the Appendix, we test the sensitivity of our results to the number of awards and the budget of the program. Indeed, the advantage of ARPA-E in producing patents and publications jointly is either reduced or eliminated when only the top performers from EERE or Office of Science are included. However, this explanation for ARPA-E's productivity relies on the questionable assumption that agencies are able to accurately predict the performance of a project at the time of selection. Testing this assumption would require data from the review process at EERE and Office of Science, to determine which projects would have been funded if they had operated at a reduced size.

Other explanations for ARPA-E's advantage could be based on the agency's stated goal of bridging the gap between "basic" and "applied" research. The pool of ideas submitted to ARPA-E could differ in type and/or quality from those submitted to other DOE funding streams. ARPA-E solicitations specifically request early-stage technology ideas (see Section 2.2), and this may influence the composition of the applicant pool (e.g. more commercially active academic labs) and the types of ideas that they decide to propose (e.g. ideas perceived as unsuited for other programs). Additionally, if ARPA-E program directors tend to encourage awardees to protect their inventions, then we would expect to observe more frequent patenting. The same is true if either EERE or Office of Science program directors tend to discourage awardees from pursuing IP.

The explanations above are only a sampling and not an exhaustive list of the differences between ARPA-E, EERE, and Office of Science. Regardless of the causes that underlie our results, the central finding remains that ARPA-E funding has been frequently cited in the production of knowledge that is both useful for technology and valuable for science. This demonstrates that there is no inherent conflict between supporting science and supporting technology within the same funding organization. Furthermore, having shown an example of an agency that operates successfully at the boundary of "basic" and "applied" research, we suppose that maintaining a rigid boundary represents a missed opportunity. Funding organizations may be able to support more downstream innovation simply by expanding their mission to account for the synergy between discovery and invention.

We have shown that the division of science and technology into separate organizations is not necessary for knowledge production. However, we are not arguing, as some have (Sarewitz, 2016), that science must be directly motivated by a particular application in order to be worthwhile. Some DOE-funded efforts may be primarily expected to produce discoveries, such as the High Energy Physics program in Office of Science, which funds work on particle accelerators. Similarly, there are EERE programs that may be primarily expected to improve existing technology. We assert that, despite these expectations, research outcomes are inherently uncertain, and there should be as few barriers as possible for researchers to pursue unanticipated directions that could further DOE's mission.

Looking to other mission-driven agencies in the US government offers an example of where the close relationship between science and technology funding is already practiced. At 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). Elsewhere, the appropriate relationship between “basic” and “translational” research funding at the National Institutes of Health (NIH) continues to be debated (American Academy of Arts & Sciences, 2013); recent research finds no substantial difference in commercial patenting as a function of “basicness” for NIH grants (Li et al., 2017).

Because DOE has a mission to address challenges in energy technology, it must fund research in a way that allows science to be easily integrated with technology as needed. Long-term transformation of the energy system will require progress in both science and technology, and the urgency of that transformation demands that we eliminate frictions between them. Science and technology should share the same organizational umbrella, to maximize the chance of fruitful interactions between the two. Recent organizational changes, such as the appointment of the Under Secretary for Science and Energy and the creation of the Energy Innovation Hubs, have moved DOE in this direction.

6. Conclusion

In the course of pursuing early-stage technology R&D, ARPA-E awards have produced a significant volume of both patents and publications. Although we cannot definitively prove the presence or absence of scientific impact using publication and citation metrics, our evidence does suggest 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 may be complementary activities. Our findings run directly counter to the idea that funding research requires a choice between impact on the scientific community and practical application.

In this work, we empirically identify ARPA-E as an amalgam of “basic” and “applied” research within a single funding organization, and importantly, within individual research projects. Future research in this area could investigate the indirect impact of ARPA-E, by studying the networks of forward citations of the patents and papers that are linked by a single financial award. We plan to continue this line of study using detailed case studies to reflect the potential for market impact of ARPA-E-supported work, beyond what can be demonstrated by metrics of publishing and patenting.

Another opportunity for improvement in this line of inquiry is to obtain higher quality data on R&D awards, including detailed categorization of sponsored activity by technical area. The scope of this research could also be expanded to include the relationship between research, development, and demonstration activities at DOE. This would likely require a subjective assessment of outcomes, making use of internal program data and qualitative descriptions of progress. This type of analysis is both accurate and labor-intense (Eisenstein, 2016).

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References

110th Congress, 2007. America COMPETES Act. United States.

111th Congress, 2011. America COMPETES Act Reauthorization of 2010. United States.

95th Congress, 1978. Federal Grant and Cooperative Agreement Act of 1977. United States.

American Academy of Arts & Sciences, 2013. Arise II: Unleashing America's Research and Innovation Enterprise.

Anadón, L.D., 2012. Missions-oriented RD&D institutions in energy between 2000 and 2010: A comparative analysis of China, the United Kingdom, and the United States. Res. Policy 41, 1742–1756. doi:10.1016/j.respol.2012.02.015

Anadón, L.D., Chan, G., Bin-nun, A.Y., Narayanamurti, V., 2016. The pressing energy innovation challenge of the US National Laboratories. Nat. Energy 16117. doi:10.1038/nenergy.2016.117

ARPA-E, 2016. ARPA-E: The First Seven Years: A Sampling of Project Outcomes.

ARPA-E, 2015. Single-Pane Highly Insulating Efficient Lucid Desings (SHIELD) Funding Opportunity No. DE-FOA-0001425.

ARPA-E, 2014. Traveler Response Architecture using Novel Signaling for Network Efficiency in Transportation (TRANSNET) Funding Opportunity No. DE-FOA-0001199.

ARPA-E, 2012. Methane Opportunities for Vehicular Energy (MOVE) Funding Opportunity No. DE-FOA-0000672.

ARPA-E, 2011. Green Electricity Network Integration (GENI) Funding Opportunity Number DE-FOA-0000473.

ARPA-E, 2010. Advanced Research Projects Agency-Energy FY2010 Annual Report.

Bornmann, L., Marx, W., 2012. How good is research really? EMBO Rep. 14, 226–230. doi:10.1038/embor.2013.9

Bush, V., 1945. Science - The Endless Frontier. doi:10.1038/188190d0

Byerly, R., Pielke Jr., R.A., 1995. The changing ecology of United States science. Science 269, 1531–1532. doi:10.1126/science.269.5230.1531

Dasgupta, P., David, P.A., 1994. Toward a new economics of science. Res. Policy 23, 487–521. doi:10.1016/0048-7333(94)01002-1

Defense Science Board, 2012. Report of the Defense Science Board Task Force on Basic Research.

Eisenstein, M., 2016. Academic return. Nature 533, S20–S21.

Er, S., Suh, C., Marshak, M.P., Aspuru-Guzik, A., 2015. Computational design of molecules for an all-quinone redox flow battery. Chem. Sci. 6, 845–1592. doi:10.1039/c4sc03030c

European Patent Office, United States Patent and Trademark Office, 2016. Cooperative Patent Classification Scheme 2016.08.

Fabrizio, K.R., Di Minin, A., 2008. Commercializing the laboratory: Faculty patenting and the open science environment. Res. Policy 37, 914–931. doi:10.1016/j.respol.2008.01.010

Fehder, D.C., Murray, F.E., Stern, S., 2014. Intellectual property rights and the evolution of scientific journals as knowledge platforms. Int. J. Ind. Organ. 36, 83–94. doi:10.1016/j.ijindorg.2014.08.002

Gans, J.S., Murray, F.E., 2012. Funding Scientific Knowledge: Selection, Disclosure, and the Public-Private Portfolio, in: Lerner, J., Stern, S. (Eds.), The Rate and Direction of Inventive Activity

Revisited. University of Chicago Press, pp. 51–103.

Gans, J.S., Murray, F.E., Stern, S., 2013. Contracting Over the Disclosure of Scientific Knowledge: Intellectual Property and Academic Publication (No. 19560).

Godin, B., 2006. The Linear Model of Innovation: The Historical Construction of an Analytical Framework. Sci. Technol. Human Values 31, 639–667. doi:10.1177/0162243906291865

Huskinson, B., Marshak, M.P., Suh, C., Er, S., Gerhardt, M.R., Galvin, C.J., Chen, X., Aspuru-Guzik, A., Gordon, R.G., Aziz, M.J., 2014. A metal-free organic–inorganic aqueous flow battery. Nature 505, 195–198. doi:10.1038/nature12909

Lemley, M.A., Shapiro, C., 2005. Probabilistic Patents. J. Econ. Perspect. 19, 75–98. doi:10.1257/0895330054048650

Li, D., Azoulay, P., Sampat, B.N., 2017. The applied value of public investments in biomedical research. Science 10.

Lin, K., Chen, Q., Gerhardt, M.R., Tong, L., Kim, S.B., Eisenach, L., Valle, A.W., Hardee, D., Gordon, R.G., Aziz, M.J., Marshak, M.P., 2015. Alkaline quinone flow battery. Science 349, 1529–1532. doi:10.1126/science.aab3033

Malakoff, D., 2014. U.S. Senate approves new DOE science undersecretary. Science.

Murray, F.E., 2002. Innovation as co-evolution of scientific and technological networks: exploring tissue engineering. Res. Policy 31, 1389–1403. doi:10.1016/S0048-7333(02)00070-7

Murray, F.E., Stern, S., 2007. Do formal intellectual property rights hinder the free flow of scientific knowledge? J. Econ. Behav. Organ. 63, 648–687. doi:10.1016/j.jebo.2006.05.017

Narayanamurti, V., Odumosu, T., 2016. Cycles of Invention and Discovery: Rethinking the Endless Frontier. Harvard University Press, Cambridge, MA.

Narayanamurti, V., Odumosu, T., Vinsel, L., 2013. RIP: The Basic/Applied Research Dichotomy. Issues Sci. Technol. 29, 31–36.

National Science Foundation, National Center for Science and Engineering Statistics, 2015. Federal R&D Funding, by Budget Function: Fiscal Years 2014–16 [WWW Document]. URL https://www.nsf.gov/statistics/fedbudget/

Nelson, R.R., 1962. The Link Between Science and Invention: The Case of the Transistor, in: The Rate and Direction of Inventive Activity: Economic and Social Factors. Princeton University Press, pp. 549–584.

OECD, 2015. Frascati Manual 2015: Guidelines for Collecting and Reporting Data on Research and Experimental Development. doi:10.1787/9789264239012-en

Office of Basic Energy Sciences, 2016. BES Organizational Chart, Dec. 2016 [WWW Document]. URL https://science.energy.gov/bes/about/staff/

Office of Energy Efficiency & Renewable Energy, 2016. EERE Organizational Chart, Oct. 28, 2016 [WWW Document]. URL https://energy.gov/eere/downloads/office-energy-efficiency-and-renewable-energy-organization-chart

Rassenfosse, G. De, Jaffe, A.B., Webster, E., 2016. Low-quality Patents in the Eye of the Beholder: Evidence from Multiple Examiners (No. 22244).

Rosenberg, N., 1990. Why Do Firms Do Basic Research (With Their Own Money)? Res. Policy 19, 165–174.

Sarewitz, D., 2016. Saving Science. New Atl. Spring/Sum, 5.

Stokes, D.E., 1997. Pasteur’s Quadrant. Brookings Institution Press, Washington, DC.

U.S. Department of Energy, 2016. Department of Energy FY 2017 Congressional Budget Request - Budget in Brief.

U.S. Department of Energy, 2015. Department of Energy organizational chart, 14 Jul 2015 [WWW Document]. URL https://energy.gov/leadership/organization-chart

U.S. Department of Energy, 2014. Basic Energy Sciences Summary Report. doi:10.1021/nl203332e.

U.S. Department of Energy, n.d. Hubs [WWW Document]. URL https://www.energy.gov/science-innovation/innovation/hubs (accessed 12.21.16).

Williams, R., 2012. Using the margins command to estimate and interpret adjusted predictions and marginal effect. Stata J. 12, 308–331.